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How 2 HAWC2, the user's manual

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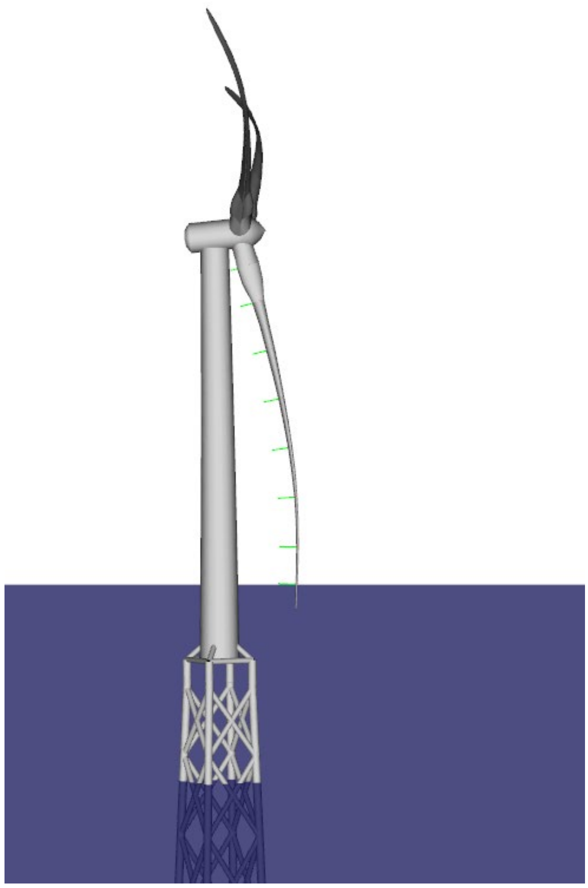
Edited by the DTU Wind Energy HAWC2 Development Team

Risø-R-1597(ver. 13.2)(EN)



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Abstract:
The report contains the user's manual for the aeroelastic code HAWC2. The code is intended for calculating wind turbine response in time domain and has a structural formulation based on multi-body dynamics. The aerodynamic part of the code is based on the blade element momentum theory, but extended from the classic approach to handle dynamic inflow, dynamic stall, skew inflow, shear effects on the induction and effects from large deflections. It has mainly been developed within the years 2003-2006 at the aeroelastic design research programme at Risoe, National laboratory Denmark, but is continuously updated and improved.
This manual is updated for HAWC2 version 13.2 and wkin.dll version 2.8.5.

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Contents

1 Preface

The HAWC2 code is a code intended for calculating wind turbine response in time domain. It has been developed within the years 2003-2006 at the aeroelastic design research programme at Risoe, National laboratory Denmark.

The structural part of the code is based on a multibody formulation where each body is an assembly of Timoshenko beam elements. The formulation is general which means that quite complex structures can be handled and arbitrary large rotations of the bodies can be handled. The turbine is modeled by an assembly of bodies connected with constraint equations, where a constraint could be a rigid coupling, a bearing, a prescribed fixed bearing angle etc. The aerodynamic part of the code is based on the blade element momentum theory, but extended from the classic approach to handle dynamic inflow, dynamic stall, skew inflow, shear effects on the induction and effects from large deflections. Several turbulence formats can be used. Control of the turbine is performed through one or more DLL's (Dynamic Link Library). The format for these DLL's is also very general, which means that any possible output sensor normally used for data file output can also be used as a sensor to the DLL. This allows the same DLL format to be used whether a control of a bearing angle, an external force or moment is placed on the structure. The code has internally at Risoe been tested against the older validated code HAWC, the CFD code Ellipsys and numerous measurements. Further on detailed verification is performed in the IEA annex 23 and annex 30 research project regarding offshore application. Scientific papers involving the HAWC2 is normally posted on the www.hawc2.dk homepage, where the code, manual and more can be downloaded. During the programming of the code a lot of focus has been put in the input checking so hopefully meaningful error messages are written to the screen in case of lacking or obvious erroneous inputs. However since the code is still constantly improved we appreciate feedback from the users – both good and bad critics are welcome. The manual is also constantly updated and improved, but should at the moment cover the description of available input commands.

2 Acknowledgements

The code has been developed primarily by internal funds from Risø National Laboratory – Technical University of Denmark, but the research that forms the basis of the code is mainly done under contract with the Danish Energy Authority. The structural formulation of the model is written by Anders M. Hansen as well as the solver and the linking between external loads and structure. The anisotropic FPM beam model is written by Christian Pavese, Taeseong Kim and Anders M. Hansen. The aerodynamic BEM module is written by Helge A. Madsen, Torben J. Larsen and Georg R. Pirrung. Three different stall models are implemented where the S.Ø. (Stig Øye) model is implemented by Torben J. Larsen, the mhh Beddoes model is written by Morten Hansen, Mac Gaunaa and Georg R. Pirrung and the ateflap model used for trailing edge flaps is written by Mac Gaunaa and Peter Bjørn Andersen and has later been rewritten by Leonardo Bergami. The near wake model has been developed by Georg R. Pirrung, Ang Li, Helge Aa. Madsen and Peter B. Andersen. The wind and turbulence module as well as the soil and DLL modules are written by Torben J. Larsen. The hydrodynamic module is written by Anders M. Hansen and Torben J. Larsen. The turbulence generator is written by Jacob Mann and the WAsP Team and converted into a DLL by Peter Bjørn Andersen. The dynamic wake meandering module is written by Helge A. Madsen, Gunner Larsen and Torben J. Larsen, and has been further maintained by Jaime Liew. The eigenvalue solver is implemented by Anders M. Hansen and John Hansen. The Gitlab repository including automatic testing and compilation was created by Mads M. Pedersen and Anders M. Hansen. Torben J. Larsen and Anders M. Hansen were the main authors of the manual up to version 4.7, and the main developers of HAWC2 up to version 12.8. Maintenance of the codebase, webpage and the manual is performed by the HAWC2 development team at DTU Wind Energy.

3 Contributors

Contributors to this manual and the HAWC2 code include but are not limited to:

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4 Getting started with HAWC2

This section contains some basic overview information and tips on debugging files when running HAWC2. A more detailed description of the format of the input file is discussed in Section 5.

4.1 Running HAWC2

HAWC2 is run by calling the HAWC2 executable from a Windows Command Prompt on the input file, which has a `.htc` file extension (see Section 5):

```
> <path to HAWC2 executable> <path to htc file>
```

For example, if the current working directory of the Command Prompt contains both your HAWC2 executable and an input file called `turbine_model.htc` (which is not a recommended folder structure, see below), the command to run HAWC2 would be

```
> HAWC2MB.exe turbine_model.htc
```

Important! Any relative paths in the `htc` file will be defined with respect to the current working directory of the Command Prompt, *not* with respect to the file's location.

To identify which version of HAWC2 is on the system, the "–version" flag can be used. This will make HAWC2 print the version information of the program, and terminate without throwing an error. An example of the call and output is shown below. This functionality is available from version 13.

```
> HAWC2MB.exe --version
```

```
 ********************************************************************
 *  Build information for HAWC2MB
 *  Aeroelastic tool HAWC2MB
 *  Intel, version         2021 ,     20201112
 *  WINDOWS 32-bit
 ********************************************************************
 *  GIT-TAG        = 12.9.5
 *  GIT-BRANCH     =
 *  BUILD_TYPE     = Windows32 RELEASE
 *  BUILDER        = ContainerAdministrator
 *  COMPUTER_NAME  = RUNNER-UYZRLEJ3
 *  BUILD_DATE     = Tue 06/21/2022
 ********************************************************************
```

4.2 Folder structure

HAWC2 does not assume any folder structure, so the executable and the input file can be located anywhere that is accessible by the Command Prompt. However, it is often best to separate different wind turbine models so that their results do not overwrite each other. It can also be nice to separate the HAWC2 executable from the input/output files in order to keep the directories as clean as possible.

One way to do this is to place HAWC2 and all its required DLLs in one directory and all of the files related to a specific turbine model in another directory. Let us demonstrate this with an example. Assume that we have placed the HAWC2 executable and all related DLLs in `C:\hawc2\`. We desire to run an htc file, called `input_a.htc`, that is located in `C:\Documents\turbine_models\prototype_a\htc\`. However, the htc file contains relative paths that are defined with respect to the `prototype_a\` directory. In this case, we must first change the working directory to the `prototype_a\` directory so that the relative paths in the htc file point to the correct files, and then we can call the HAWC2 executable on the input files using an absolute path. The commands for this example would be as follows:

```
> cd C:\Documents\turbine_models\prototype_a\
> C:\hawc2\HAWC2MB.exe .\htc\input_a.htc
```

4.3 Debugging models

Although HAWC2 is run from the Command Prompt, the errors that are printed to it when something goes wrong are often not illuminating to the average user. If something goes wrong with your model, you should first check the output log to see what warnings and errors are printed there. The output log is a text file ending in `.log`, and its location is determined by the `logfile` option in the `simulation` block in the htc file.

One of the most common errors for new users is having the wrong working directory in the Command Prompt, in which case the log file will state that it could not find the requested data files. Other common errors when running time-marching simulations include bad simulation parameters that lead to non-convergence or incorrect definitions of body properties. Regardless, your first step when debugging a model should always be to look at the log file to determine what went wrong. If you cannot find the source of your problem, you can email the HAWC2 support address (hawc2@windenergy.dtu.dk) to ask for help.

Important! HAWC2 is a flexible software with many different simulation options, so building a model from the ground up is complicated and not recommended. We recommend starting from a working model (see the HAWC2 website to download a working wind turbine model) and incrementally making changes as needed.

5 General input layout

HAWC2 takes as input a text file with an `.htc` file extension. The HAWC2 input format is written in a form that forces the user to write the input commands in a structured way so aerodynamic commands are kept together, structural commands the same, etc. The order of the blocks does not matter.

The input commands are divided into command blocks, which are defined using a begin-end syntax. Each line must end with a semi colon ";" which gives the possibility for writing comments and the end of each line after the semi colon. The command lines can be written with any desired mix of capital or small letters because inside the code all lines are transformed into small letters. This could be important if something case-sensitive is written (e.g., the name of a subroutine within a DLL).

Important! All lines in an htc file must end with a semicolon, even if they are empty. You may insert whitespace between blocks to improve readability by having a line that is just a semicolon.

In the next chapters, the input commands are explained for every part of the code. The commands are separated into "main block" commands (namely, those that belong to a begin-end command block that is not part of a higher-level begin-end block) and "sub command blocks" (those that belong to a begin-end block included within another block). An example is printed below.: "simulation" is a main command block and "newmark" is a sub command block.

```
begin simulation;
  time_stop    100.0 ;
  solvertype   2 ;    (sparse newmark)
;
  begin newmark;
    beta      0.27;
    gamma     0.51;
    deltat    0.02;
  end newmark;
end simulation;
```

5.1 Continue_in_file option

A feature from version 6.0 and newer is the possibility of continuing reading of the main input file into another. The command word continue_in_file followed by a file name causes the program to open the new file and continue reading of input until the command word exit. When exit is read the reading will continue in the previous file. An infinite number of file levels can be used. The HAWC2 input format is written in a form that forces the user to write the input commands in a structured way so aerodynamic commands are kept together, structural commands the same etc.

Command name	Explanation
continue_in_file	1. File name (and path) to sublevel input file
exit	End of input file. Input reading is continued in higher level input file.

6 HAWC2 version handling

The HAWC2 code is still frequently updated and version handling is therefore of utmost importance to ensure quality control. For every new released version of the code a new version number is hard coded in the source. This number can be found by executing the HAWC2.exe file without any parameters. The version number is echoed to screen. The same version number is also written to every result file no matter whether ASCII or binary format is chosen.

All information covering the different code versions has been made. These data are listed in appendix F.

7 Coordinate systems

The global coordinate system is located with the z-axis pointing vertical downwards. The x and y axes are horizontal to the side. When wind is submitted, the default direction is along the global y-axes. Within the wind system meteorological u,v,w coordinates are used, where u is the mean wind speed direction, v is horizontal and w vertical upwards. When x,y,z notation is used within the wind coo. this refers directly to the u,v,w definition. Every substructure and body (normally the same) is equipped with its own coordinate system with origo in node1 of this structure. The structure can be arbitrarily defined regarding orientation within this coordinate system. Within a body a number of structural elements are present. The orientation of coordinate systems for these elements are chosen automatically by the program. The local z axis is from node 1 to 2 on the element. The coordinate system for the blade structures must be defined with the z axis pointing from the blade root and outwards, x axis in the tangential direction of rotation and y axis from the pressure side towards the suction side of the blade profiles. This is in order to make the linkage between aerodynamics and structure function.

In order to make a quick check of the layout of the structure the small program “animation.exe” can be used (this requires than an animation file has been written using the command animation in the Simulation block). The view option in this program is handled by keyboard hotkeys:

Animation Hotkeys:

```
translate: (shift)+{x,y,z}
rotate: arrow keys
rotate about line-of-sight: ctrl+left/right
zoom in: ctrl+up
zoom out: ctrl+down
amplify displacement (only for animation of natural frequencies): +
decrease displacement (only for animation of natural frequencies): -
```

If the animation does not start, press “s”

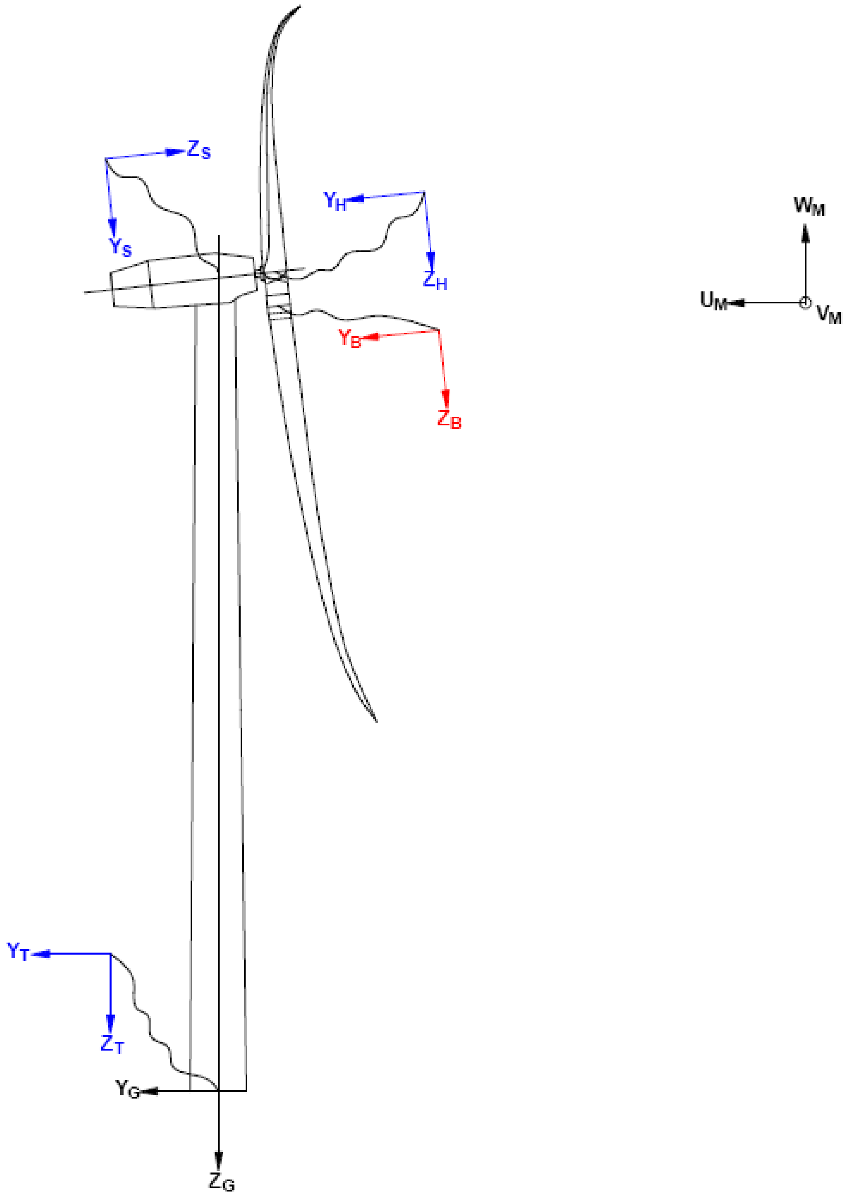


Figure 1: Illustration of coordinate system as result of user input from example in appendix A: Example of main input file. There are two coordinate systems in black which are the default coordinate systems of global reference and default wind direction. The blue coordinate systems are main body coordinate systems attached to node 1 of the substructure, the orientation of these are fully determined by the user. The red coordinate systems are also defined by the user, but in order to make the linkage between aerodynamic forces and structure work these have to have the z from root to tip, x in chordwise direction and y towards the suction side.

8 Simulation

8.1 Convergence parameters and time step

HAWC2 uses a (sparse) Newmark solver to solve the equations of motion. Convergence in HAWC2 is defined as fulfulling all 3 of the following criteria at a given time step:

1. The root-sum-of-squared-error (RSSE) of the residuals on the internal-external forces/moments in the system is below a specified threshold.
2. The RSSE of the increment in the state vector is below a specified threshold.
3. The RSSE of the constraint equations in the system is below a specified threshold.

A user should specify convergence parameters and a time step that are relevant for their system to ensure proper convergence. E.g., smaller and/or stiffer systems may require smaller time steps, or a system with smaller external loads might need a reduced threshold on the internal-external forces/moments and state increment. One possible way to determine these parameters for your model could be:

1. Reduce the time step and simulate the response. If the response has changed significantly, repeat this step until the response does not change with a reduced time step.
2. Reduce the convergence thresholds until there are 2 to 3 iterations for each time step.
3. If the response has changed significantly from Step 1, return to step 1 and repeat.

8.2 Main command block - Simulation

Obl.	Command name	Explanation
*	time_stop	1. Simulation length [s]
	solvertype	1. Solver type (1=dense Newmark (default, more robust option), 2=sparse Newmark (faster and recommended, new in version 12.7))

	initial_condition	1. Type of initial condition to use (1=undeflected (default), 2=static (available since version 13.0)). With undeflected initial conditions, the position of the nodes at the beginning of the simulation is defined by the c2_def and orientation of each main body. Setting this parameter to 2 will cause HAWC2 to solve a nonlinear static problem at the beginning of the simulation, and use this deflected configuration as initial condition. Only some forcing terms are considered for this simulation, namely: gravity, inertia, aerodynamics, hydrodynamics and external system constraints. Extending the static solver to support general HAWC2 models is under development. Generic controllers are not yet supported, but the static solver is verified to work with the echo dll, using “general constant”. This command is suitable to simulate a turbine with a fixed pitch and rotor speed. The pitch is set in the relative rotation command. Please remember that for the publicly available hawc2 models, a 5 degree pitch to feather corresponds to a rotation about the pitch axis by minus 5 degrees as specified in the relative rotation command. The rotor speed is set with “orientation / relative / mbdy2_ini_rotvec_d1” *and* “constraint / bearing3 / omegas” which must be set to the same value. Setting the initial rotor speed via “orientation / base / mbdy_ini_rotvec_d1” is also supported. The convergence history of the static solution is written in the log file. The number of iterations is controlled by “max_iterations”, while the tolerances by “convergence_limits”. The commands for iterations and tolerances of the aerodynamic part of the static solution are described in the aerodynamics section of the manual.
	solver_relax	1. Relaxation parameter on increment within a timestep. Can be used to make difficult simulation run through solver when parameter is decreased, however on the cost of simulation speed. Default=1.0
	on_no_convergence	Parameter that informs solver of what to do if convergence is not obtained in a time step. 1. ’stop’: simulation stops – default. ’continue’: simulation continues, error message is written.
	convergence_limits	Convergence limits that must be obtained at every time step. See Sec. 8.1. 1. epsresq, residual on internal-external forces, default=10.0 2. epsresd, residual on increment, default=1.0 3. epsresg, residual on constraint equations, default=1E-7
	max_iterations	1. Number of maximum iterations within a time step.
	animation	Included if animation file is requested 1. Animation file name incl. relative path. E.g. ./animation/animation1.dat
	visualization	Included if simulation visualization file is requested 1. Visualization file name incl. relative path. E.g. ./visualization/example.hdf5; (optional: 2. time at which the visualization output starts [s]) (optional: 3. time at which the visualization output ends [s])
	logfile	Included if a logfile is requested internally from the htc command file. 1. Logfile name incl. relative path. E.g. ./logfiles/log1.txt

	log_deltat	If specified, iteration statitics is written to the log(file) every log_deltat seconds. Otherwise a log line is printed every time step. 1. Time between output to logfile [s], e.g. 2.5
	default_gravity	If specified, the gravity acceleration provided will be used for all bodies and water properties, except if gravity is specifically provided for individual bodies or water properties. 1. Gravity acceleration, default 9.81 m/s^2.

8.3 Sub command block - newmark

Obl.	Command name	Explanation
	beta	1. beta value (default=0.27)
	gamma	1. gamma value (default=0.51)
*	deltat	1. time increment [s]
	symmetry	1. Solver assumption regarding mass, damping and stiffness matrices (1=symmetric (default), 2=assymetric (recommended for offshore structures). When hydrodynamic loading is applyed this parameter will automatically change to 2.)

9 Structural input

9.1 Main command block - new_htc_structure

Obl.	Command name	Explanation
	beam_output_file_name	Write the beam properties for all bodies. 1. File name including relative path to file where the beam data are listed (output) (example ./info/beam.dat)
	body_output_file_name	Write the initial conditions and inertia matrix for all bodies. 1. File name including relative path to file where the body data are listed (output) (example ./info/body.dat)
	struct_inertia_output_file_name	For all bodies, write the inertia matrix, with respect to the center of gravity, in global and local coordinates. 1. File name including relative path to file where the global inertia information data are listed (output) (example ./info/inertia.dat)
	body_matrix_output	Write the assembled stiffness, damping and mass matrices for all bodies. 1. Folder name where the bodies structural matrices are listed (example ./info/body).
	element_matrix_output	Write the elements stiffness, damping and mass matrices. 1. File name including relative path to file where the elements structural matrices are listed (example ./info/element.dat).
	constraint_output_file_name	Write the initial conditions of the constraints in global coordinates. 1. File name including relative path to file where the constraint data are listed (output). (example ./info/constraint.dat)
	body_eigenanalysis_file_name	Do the eigenvalue analysis for all bodies. Deprecated, use system_eigenanalysis instead. Write the damped frequency, natural frequency and logarithmic decrement. The eigenvalue analysis should be the last operation in a simulation.
	structure_eigenanalysis_file_name	Do the eigenvalue analysis for the entire structure. Deprecated, use system_eigenanalysis instead. Write the damped frequency, natural frequency, logarithmic decrement and animation of the mode shapes. The eigenvalue analysis should be the last operation in a simulation. 1. File name including relative path to file where the results of an complete turbine eigenanalysis are listed (example ./info/eigen_all.dat). Animation files are placed in the same directory of the file name. 2. Optional parameter determining if structural damping is included in the eigenvalue calculation or not. (0=damping not included, most robust method, 1=damping included default)
	system_eigenanalysis	Do the eigenvalue analysis for the entire structure, including external systems attached, eg. mooring lines. Constraint equations are also fully included in the analysis. Write the damped frequency, natural frequency, logarithmic decrement and animation of the mode shapes. The eigenvalue analysis should be the last operation in a simulation. 1. File name including relative path to file where the results of an complete turbine eigenanalysis are listed (example ./info/eigen_all.dat). Animation files are placed in the same directory of the file name.

		2. (optional) Parameter determining if structural damping is included in the eigenvalue calculation or not. (0=damping not included, most robust method, 1=damping included default) 3. (optional) Number of modes outputted. 4. (optional) Time for when the eigenanalysis is carried out. Eg. after a settling of a floating system.

9.2 Sub command block - main_body

This block can be repeated as many times as needed. For every block a new body is added to the structure. A main body is a collection of normal bodies which are grouped together for bookkeeping purposes related to input output. When a main body consist of several bodies the spacing the name of each body inherits the name of the master body and is given an additional name of '_#', where # is the body number. An example could be a main body called 'blade1' which consist of two bodies. These are then called 'blade1_1' and 'blade1_2' internally in the code. The internal names are only important if (output) commands are used that refers to the specific body name and not the main body name.

Obl.	Command name	Explanation
*	name	1. Main_body identification name (must be unique)
*	type	1. Element type used (options are: timoschenko)
*	nbodies	1. Number of bodies the main_body is divided into (especially used for blades when large deformation effects needs attention). Equal number of elements on each body, eventually extra elements are placed on the first body.
*	node_distribution	1. Distribution method of nodes and elements. Options are: "uniform" nnodes. Where uniform ensures equal element length and nnodes are the node numbers. "c2_def", which ensures a node a every station defined with the sub command block c2_def.
	damping	Original damping model that can only be used when the shear center location equals the elastic center to ensure a positive definite damping matrix. It is recommended to use the damping_posdef command instead. Rayleigh damping parameters containing factors that are multiplied to the mass and stiffness matrix respectfully. ! Pay attention, the mass proportional damping is not contributing when a mbdy consist of multiple bodies ! 1. M_x 2. M_y 3. M_z 4. K_x 5. K_y 6. K_z NOTE: This damping model cannot be used with the Fully Populated Matrix ("FPM 1", see below) beam element!
	damping_posdef	Rayleigh damping parameters containing factors. M_x, M_y, M_z are constants multiplied on the mass matrix diagonal and inserted in the damping matrix. K_x, K_y, K_z are factors multiplied on the moment of inertia I_x, I_y, I_z in the stiffness matrix and inserted in the damping matrix. Parameters are in size approximately the same as the parameters used with the original damping model written above.

		! Pay attention, the contribution from mass proportional damping is limited when a mbdy consist of multiple bodies ! 1. M_x 2. M_y 3. M_z 4. K_x 5. K_y 6. K_z NOTE: This damping model cannot be used with the Fully Populated Matrix (“FPM 1”, see below) beam element!
	damping_aniso	Mixed mass/stiffness proportional and stiffness proportional damping parameters containing factors. η_x^m, η_y^m, η_t^m are constants multiplied on a mixed mass/stiffness matrix diagonal and inserted in the damping matrix. η_x^s, η_y^s, η_t^s are factors multiplied on the moment of inertia I_x, I_y, I_z in the stiffness matrix and inserted in the damping matrix. ! Pay attention, the mass proportional damping is not contributing when a mbdy consist of multiple bodies ! Damping_aniso will give a similar damping to damping_posdef if 1) only stiffness proportional damping is used (first three coefficients in both models are zero) and 2) the 4th and 5th parameters are swapped ($n_y^s = K_x$ and $n_x^s = K_y$) ! See the command for the corrected version of damping_aniso below ! 1. η_x^m 2. η_y^m 3. η_t^m 4. η_x^s 5. η_y^s 6. η_t^s
	damping_aniso_v2	Identical usage as damping_aniso, but a minor bug in the torsional damping computation has been fixed.
	damping_file	Pre-generated damping read from file - the file can be generated by the metod described in Section C. 1. File name.
	copy_main_body	Command that can be used if properties from a previously defined body shall be copied. The name command still have to be present, all other data are overwritten. 1. Main_body identification name of main_body that is copied.
	gravity	1. Specification of gravity (directed towards zG). NB! this gravity command only affects the present main body. Default=9.81 [m/s^2]
	concentrated_mass	Concentrated masses and inertias can be attached to the structure. The offset distance from the node to the center of mass is given in the body’s coordinates system. The moments and products of inertia is given around the center of mass in the body’s coordinates system. 1. Node number to which the inertia is attached. 2. Offset distance x-direction [m] 3. Offset distance y-direction [m] 4. Offset distance z-direction [m] 5. Mass [kg] 6. I_{xx} [kg m^2]

		7. I_{yy} [kg m^2] 8. I_{zz} [kg m^2] 9. I_{xy} [kg m^2] – optional 10. I_{xz} [kg m^2] – optional 11. I_{yz} [kg m^2] – optional
	external_bladedata_dll	Blade structural data are found in an external encrypted dll. If this command is present only these other command lines need to be present (name, type, nbodies, node_distribution and a damping command line). 1. Company name (that has been granted a password, eg. dtu). 2. Password for opening this specific dll, eg. test1234 3. path and filename for the dll. eg. ./data/encr_blade_data.dll

9.2.1 Sub sub command block – timoschenko_input

Block containing information about location of the file containing distributed beam property data and the data set requested.

Obl.	Command name	Explanation
*	filename	1. Filename incl. relative path to file where the distributed beam input data are listed (example ./data/hawc2_st.dat)
	FPM	Logic command for Fully Populated Matrix beam element: 1. Write “1” to read a structural input file based on the fully populated stiffness matrix. Write “0” for the original beam model If the command is neglected, HAWC2 will assume that the structural input file is based on the original beam model
	mass_scale_method	Specify how to scale total mass of a main body. 1. 0 or 1 (default) For method 1 the mass is adjusted for the entire main body such that the static moment around the first node is the same as when integrating the varying mass properties in the st file. Method 0 means no scaling is applied. See paragraph below for more information. Method 1 is the default option if this command is not present.

Note on mass scaling method: Scaling method 1 has historically been the default scaling method in HAWC2 to assure that, for example, the edge-wise gravity loads of the blade are consistent with the st input. In the st input file the mass varies linearly between the data points while the elements of a body (following the discretization from the c2_def section) have a constant mass. Depending on the c2_def discretization and the st file mass distribution HAWC2 will have to choose to either keep the total integrated mass or the static mass moment consistent between them.

There is a simple example with three different mass distributions available at `https://gitlab.windenergy.dtu.dk/HAWC2Public/examples/-/tree/master/hawc2/structure/static_mass_moment` that demonstrates how the mass scaling method behaves.

Mass method scaling method 1 can be expressed mathematically as follows:

$$m_{eigen} = \frac{2\sqrt{m_x^2 + m_y^2 + m_z^2}}{L\sqrt{L_x^2 + L_y^2 + L_z^2}} \quad \text{, where}$$

$$m_x = \int_0^L r_x m \, dr \text{ , } m_y = \int_0^L r_y m \, dr \text{ , } m_z = \int_0^L r_z m \, dr$$

$$r_x = \sqrt{y^2 + z^2} \text{ , } r_y = \sqrt{x^2 + z^2} \text{ , } r_z = \sqrt{x^2 + y^2}$$

$$L_x = \sqrt{p_y^2 + p_z^2} \text{ , } L_y = \sqrt{p_x^2 + p_z^2} \text{ , } L_z = \sqrt{p_x^2 + p_y^2}$$

p_x, p_y, p_z are element mid point coordinates

L is element length, m is mass per unit length

9.2.2 Sub sub command block – c2_def

In this command block the definition of the centerline of the main_body is described (position of the half chord, when the main_body is a blade). The input data given with the sec commands below is used to define a continous differentiable line in space using akima spline functions. This centerline is used as basis for local coordinate system definitions for sections along the structure. If two input sections are given it is assumed that all points are on a straight line. If three input sections are given points are assumed to be on the line consisted of two straight lines. If four or more input sections are given points are assumed to be on an akima interpolated spline. This spline will include a straight line if a minimum of three points on this line is defined.

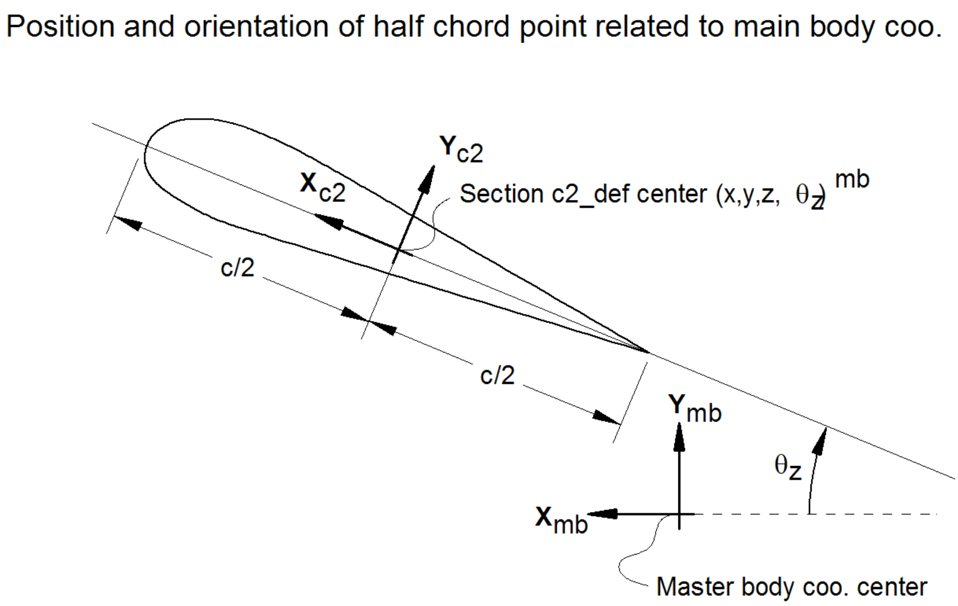
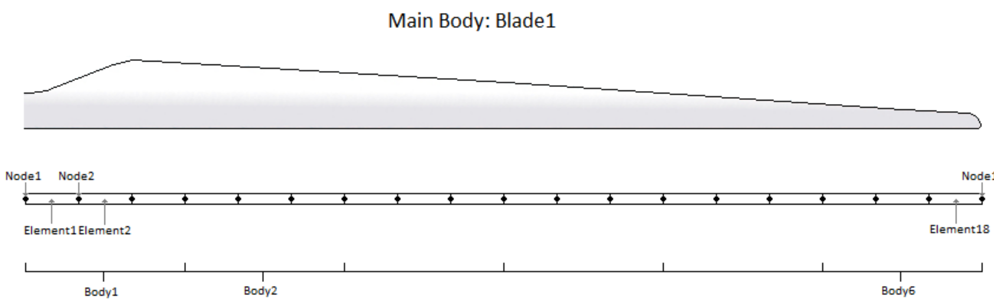


Figure 2: Illustration of c2_def coordinate system related to main body coordinates. The blade z-coordinate has to be positive from root towards the tip.

Obl.	Command name	Explanation
*	nsec	Must be the present before a “sec” command. 1. Number of section commands given below
*	sec	Command that must be repeated “nsec” times. Minimum 4 times. 1. Number 2. x-pos [m] 3. y-pos [m] 4. z-pos [m] 5. θ_z [deg]. Angle between local x-axis and main_body x-axis in the main_body x-y coordinate plane. For a straight blade this angle is the aerodynamic twist. Note that the sign is positive around the z-axis, which is opposite to traditional notation for etc. a pitch angle.

Here is an illustration of how a blade can be defined with respect to discretisation of bodies, nodes and elements.



Here is an example of this written into the htc-input file.

```
begin main_body;
name        blade1 ;
type        timoschenko ;
nbodies     6 ;
node_distribution    c2_def;
damping_posdef   1.17e-4 5.77e-5 6.6e-6 6.6e-4 5.2e-4 6.5e-4 ;
begin timoschenko_input ;
filename ./data/st_file.txt ;
  FPM 0;  (optional, when parameter is 0)
  set 1 1 ;                set subset
end timoschenko_input;
begin c2_def;              Definition of centerline (main_body coordinates)
  nsec 19 ;
sec 1   -0.0000  0.0000  0.000     0.000 ;
sec 2   -0.0041  0.0010  3.278   -13.590 ;
sec 3   -0.1048  0.0250  6.556   -13.568 ;
sec 4   -0.2582  0.0492  9.833   -13.564 ;
sec 5   -0.4694  0.0587  13.111  -13.546 ;
sec 6   -0.5689  0.0957  16.389  -11.406 ;
sec 7   -0.5455  0.0883  19.667  -10.145 ;
sec 8   -0.5246  0.0732  22.944   -9.043 ;
sec 9   -0.4362  0.0669  26.222   -7.843 ;
sec 10  -0.4644  0.0554  29.500   -6.589 ;
sec 11  -0.4358  0.0449  32.778   -5.447 ;
sec 12  -0.4859  0.0347  36.056   -4.234 ;
sec 13  -0.3759  0.0265  39.333   -3.545 ;
sec 14  -0.3453  0.0130  42.611   -2.223 ;
sec 15  -0.3156  0.0084  45.889   -1.553 ;
sec 16  -0.2791  0.0044  49.167   -0.934 ;
sec 17  -0.2675  0.0017  52.444   -0.454 ;
```

```
sec 18  -0.1785  0.0003  55.722   -0.121 ;
sec 19  -0.1213  0.0000  59.000   -0.000 ;
 end c2_def ;
end main_body;
```

Format definition of file with distributed beam properties (st file) The format of this file, which in the old HAWC code was known as the hawc_st file, is changed slightly for the HAWC2 new_htc_structure format. The file is a text file in which the structural parameters are organized into main sets and sub sets. The main set is located after a “#” sign followed by the main set number. Within a main there can be as many subsets as desired. They are located after a “$” sign followed by the local set number. The next sign of the local set number is the number of lines in the following rows that belong to this sub set.

There are two types st_file:

- The st_file for the original HAWC2 beam element. Input parameters for this model are reported in Table 1 HAWC2 original beam element structural data.
- The st_file for the new anisotropic FPM beam element. Input parameters are reported in Table 2 New HAWC2 anisotropic beam element structural data.

Please note! The first column in the datasets, the curved-length distance from the main body’s first node, *is normalized by HAWC2* using the curved length defined by the x, y and z coordinates given in the c2_def block in the htc file. In other words, if your curved length in the st file goes from 0 to 100 but the curved length defined by the c2_def coordinates has a max curved length of 50, then the st-file curved length will be normalized such that it goes from 0 to 50 and a warning will be printed in the log file. The curved length in the st file should start from 0. We recommend having consistent curved lengths in the st and htc files; consider using the `beam_output_file_name` to verify the lengths. For more information on how HAWC2 handles differing node locations in the htc file and st file, please see the structural module in the HAWC2 training course.

In general all centers are given according to the $C_{1/2}$ center location and all other are related to the principal bending axes. For the anisotropic beam element, centers are given according to the $C_{1/2}$ center location, but the cross sectional stiffness matrix is given at the elastic center rotated along the principal bending axes.

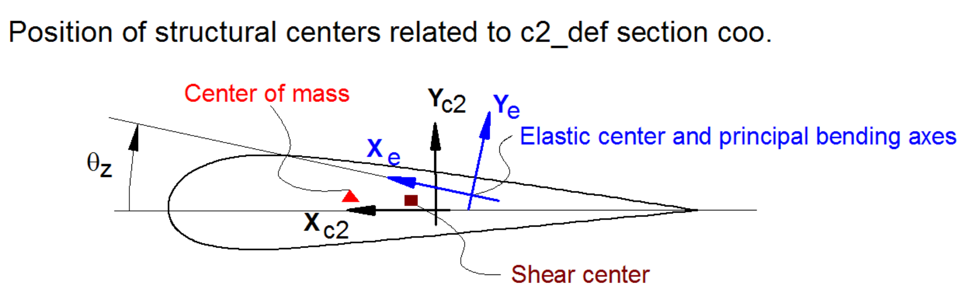


Figure 3: Illustration of structural properties that in the input files are related to the c2 coordinate system.

A small explanation about radius of gyration (also called radius of inertia) and the area moment of inertia (related to stiffness) is shown below in N.5 and N.11

An example of a st original beam formulation input file can be seen on the next page. The most important features to be aware of are colored with red.

Table 4: HAWC2 original beam element structural data

Column	Parameter
1	r, curved length distance from main_body node 1 [m]. HAWC2 normalizes this by the curved length defined in c2_def.
2	m, mass per unit length [kg/m]
3	x_m, x_{c2}-coordinate from $C_{1/2}$ to mass center [m]
4	y_m, y_{c2}-coordinate from $C_{1/2}$ to mass center [m]
5	r_{ix}, radius of gyration related to elastic center. Corresponds to rotation about principal bending x_e axis [m]
6	r_{iy}, radius of gyration related to elastic center. Corresponds to rotation about principal bending y_e axis [m]
7	x_s, x_{c2}-coordinate from $C_{1/2}$ to shear center [m]. The shear center is the point where external forces only contributes to pure bending and no torsion.
8	y_s, y_{c2}-coordinate from $C_{1/2}$ to shear center [m]. The shear center is the point where external forces only contributes to pure bending and no torsion.
9	E, modulus of elasticity $[N/m^2]$
10	G, shear modulus of elasticity $[N/m^2]$
11	I_x, area moment of inertia with respect to principal bending x_e axis $[m^4]$. This is the principal bending axis most parallel to the x_{c2} axis
12	I_y, area moment of inertia with respect to principal bending ye axis $[m^4]$
13	K, torsional stiffness constant with respect to ze axis at the shear center $[m^4/rad]$. For a circular section only this is identical to the polar moment of inertia.
14	k_x shear factor for force in principal bending x_e direction [-]
15	k_y, shear factor for force in principal bending ye direction [-]
16	A, cross sectional area $[m^2]$
17	θ_z, structural pitch about z_{c2} axis. This is the angle between the x_{c2} -axis defined with the c2_def command and the main principal bending axis x_e. [deg]
18	x_e, x_{c2}-coordinate from $C_{1/2}$ to center of elasticity [m]. The elastic center is the point where radial force (in the z-direction) does not contribute to bending around the x or y directions.
19	y_e, y_{c2}-coordinate from $C_{1/2}$ to center of elasticity [m]. The elastic center is the point where radial force (in the z-direction) does not contribute to bending around the x or y directions.

- **N.5** r_{ix} $[m]$ Radius of inertia. Related to the Moment of Inertia I_{xx} $[kg\ m^2]$, which gives the rotation inertia, resistance to change in rotation rate:

$$I_{xx} = \int r_{ix}^2 \mathrm{d}m \quad \rightarrow \quad r = \sqrt{\frac{I_{xx}}{m}} \;= \sqrt{\frac{I_x}{\mathrm{A}}}$$

- **N.11** I_x $[m^4]$ Area moment of inertia with respect to x_e. It's the second moment of area $I_x = \int y^2 \mathrm{d}A$. Multiplied by Young's modulus E gives the flapwise bending stiffness:

$$\mathrm{Stiffn}_{\mathrm{flap}} = E \cdot I_x = \frac{M}{\mathrm{d}^2 w / \mathrm{d}^2 x}$$

$$\mathrm{Stiffn}_{\mathrm{edge}} = E \cdot I_y$$

$$\mathrm{Stiffn}_{\mathrm{tors}} = \mathbf{G} \cdot \mathbf{K}$$

```
1 main data sets available
-----------------------------------
Here is space for comments etc
.
.
.
-----------------------------------
#1 Main data set number 1 - an example of a shaft structure
-----------------------------------
More comments space
r          m      x_cg   y_cg ri_x   ri_y   x_sh   y_sh   E          G          I_x        I_y        K        k_x   k_y   A      theta_s  x_e    y_e
[m]        [kg/m] [m]    [m]  [m]    [m]    [m]    [m]    [N/m^2]    [N/m^2]    [N/m^4]    [N/m^4]    [N/m^4]  [-]   [-]   [m^2]  [deg]    [m]    [m]
$1 10 Sub set number 1 with 10 data rows
0.00       100    0      0    224.18 224.18 0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
0.10       100    0      0    224.18 224.18 0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
0.1001     1      0      0    0.2    0.2    0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
1.00       1      0      0    0.2    0.2    0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
1.90       1      0      0    0.2    0.2    0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
2.00       1      0      0    0.2    0.2    0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
3.00       1      0      0    0.2    0.2    0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
3.20       1      0      0    0.2    0.2    0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
4.00       1      0      0    0.2    0.2    0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
5.0191     1      0      0    0.2    0.2    0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
-----------------------------------
More comments space

r          m      x_cg   y_cg ri_x   ri_y   x_sh   y_sh   E          G          I_x        I_y        K        k_x   k_y   A      theta_s  x_e    y_e
[m]        [kg/m] [m]    [m]  [m]    [m]    [m]    [m]    [N/m^2]    [N/m^2]    [N/m^4]    [N/m^4]    [N/m^4]  [-]   [-]   [m^2]  [deg]    [m]    [m]
$2 10 As dataset 1, but stiff
0.00       100    0      0    224.18 224.18 0      0      2.10E+16   8.10E+15   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
0.10       100    0      0    224.18 224.18 0      0      2.10E+16   8.10E+15   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
0.1001     1      0      0    0.2    0.2    0      0      2.10E+16   8.10E+15   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
1.00       1      0      0    0.2    0.2    0      0      2.10E+16   8.10E+15   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
1.90       1      0      0    0.2    0.2    0      0      2.10E+16   8.10E+15   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
2.00       1      0      0    0.2    0.2    0      0      2.10E+16   8.10E+15   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
3.00       1      0      0    0.2    0.2    0      0      2.10E+16   8.10E+15   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
3.20       1      0      0    0.2    0.2    0      0      2.10E+16   8.10E+15   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
4.00       1      0      0    0.2    0.2    0      0      2.10E+16   8.10E+15   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
5.0191     1      0      0    0.2    0.2    0      0      2.10E+16   8.10E+15   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
-----------------------------------
More comments space

r          m      x_cg   y_cg ri_x   ri_y   x_sh   y_sh   E          G          I_x        I_y        K        k_x   k_y   A      theta_s  x_e    y_e
[m]        [kg/m] [m]    [m]  [m]    [m]    [m]    [m]    [N/m^2]    [N/m^2]    [N/m^4]    [N/m^4]    [N/m^4]  [-]   [-]   [m^2]  [deg]    [m]    [m]
$3 10 as data set 1 but changed mass properties
0.00       1000   0      0    2.2418 2.2418 0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
0.10       1000   0      0    2.2418 2.2418 0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
0.1001     1      0      0    0.2    0.2    0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
1.00       1      0      0    0.2    0.2    0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
1.90       1      0      0    0.2    0.2    0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
2.00       1      0      0    0.2    0.2    0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
3.00       1      0      0    0.2    0.2    0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
3.20       1      0      0    0.2    0.2    0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
4.00       1      0      0    0.2    0.2    0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
5.0191     1      0      0    0.2    0.2    0      0      2.10E+11   8.10E+10   1.00E+02   1.00E+02   0.05376  0.52  0.52  0.59   0        0.0    0.0
```

Table 5: New HAWC2 anisotropic beam element structural data

Column	
1	r, curved length distance from main_body node 1 [m]. HAWC2 normalizes this by the curved length defined in c2_def.
2	m, mass per unit length [kg/m]
3	x_m, x_{c2}-coordinate from $C_{1/2}$ to mass center [m]
4	y_m, y_{c2}-coordinate from $C_{1/2}$ to mass center [m]
5	r_{ix}, radius of gyration related to elastic center. Corresponds to rotation about principal bending x_e axis [m]
6	r_{iy}, radius of gyration related to elastic center. Corresponds to rotation about principal bending y_e axis [m]
7	θ_z, structural pitch about z_{c2} axis [deg]. This is the angle between the x_{c2} -axis defined with the c2_def command and the main principal bending axis x_e.
8	x_e, x_{c2}-coordinate from $C_{1/2}$ to center of elasticity [m]. The elastic center is the point where radial force (in the z-direction) does not contribute to bending around the x or y directions.
9	y_e, y_{c2}-coordinate from $C_{1/2}$ to center of elasticity [m]. The elastic center is the point where radial force (in the z-direction) does not contribute to bending around the x or y directions.
10	K_{11}, element 1,1 of the Cross sectional stiffness matrix $[N]$. REMEMBER: the cross sectional stiffness matrix is given at the elastic center rotated along the principal bending axes.
11	K_{12}, element 1,2 of the Cross sectional stiffness matrix $[N]$.
12	K_{13}, element 1,3 of the Cross sectional stiffness matrix $[N]$.
13	K_{14}, element 1,4 of the Cross sectional stiffness matrix $[Nm]$.
14	K_{15}, element 1,5 of the Cross sectional stiffness matrix $[Nm]$.
15	K_{16}, element 1,6 of the Cross sectional stiffness matrix $[Nm]$.
16	K_{22}, element 2,2 of the Cross sectional stiffness matrix $[N]$.
17	K_{23}, element 2,3 of the Cross sectional stiffness matrix $[N]$.
18	K_{24}, element 2,4 of the Cross sectional stiffness matrix $[Nm]$.
19	K_{25}, element 2,5 of the Cross sectional stiffness matrix $[Nm]$.
20	K_{26}, element 2,6 of the Cross sectional stiffness matrix $[Nm]$.
21	K_{33}, element 3,3 of the Cross sectional stiffness matrix $[N]$.
22	K_{34}, element 3,4 of the Cross sectional stiffness matrix $[Nm]$.
23	K_{35}, element 3,5 of the Cross sectional stiffness matrix $[Nm]$.
24	K_{36}, element 3,6 of the Cross sectional stiffness matrix $[Nm]$.
25	K_{44}, element 4,4 of the Cross sectional stiffness matrix $[Nm^2]$.
26	K_{45}, element 4,5 of the Cross sectional stiffness matrix $[Nm^2]$.
27	K_{46}, element 4,6 of the Cross sectional stiffness matrix $[Nm^2]$.
28	K_{55}, element 5,5 of the Cross sectional stiffness matrix $[Nm^2]$.
29	K_{56}, element 5,6 of the Cross sectional stiffness matrix $[Nm^2]$.
30	K_{66}, element 6,6 of the Cross sectional stiffness matrix $[Nm^2]$.

An example of a st anisotropic beam formulation input file can be seen on the next page.

#1 user_cpav generated blade

$1 31

r [0]	m [1]	x_cg [2]	y_cg [3]	ri_x [4]	ri_y [5]	x_e [6]	y_e [7]	K_11 [8]	K_12 [9]	K_13 [10]	K_14 [11]	K_15 [12]
0.0000000000e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
3.3333333333e-01	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
6.6666666667e-01	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
1.0000000000e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
1.3333333333e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
1.6666666667e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
2.0000000000e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
2.3333333333e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
2.6666666667e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
3.0000000000e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
3.3333333333e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
3.6666666667e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
4.0000000000e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
4.3333333333e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
4.6666666667e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
5.0000000000e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
5.3333333333e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
5.6666666667e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
6.0000000000e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
6.3333333333e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
6.6666666667e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
7.0000000000e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
7.3333333333e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
7.6666666667e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
8.0000000000e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
8.3333333333e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
8.6666666667e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
9.0000000000e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
9.3333333333e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
9.6666666667e+00	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0
1.0000000000e+01	8.5380000000e-02	0.0000000000e+00	0.0000000000e+00	3.4793504562e-01	2.1906122240e-01	0.0000000000e+00	0.0000000000e+00	8.8560000000e+04	0.0000000000e+00	0.0000000000e+00	0.0000000000e+00	0.0

9.2.3 Sub sub command - damping_distributed

In this command block, Rayleigh damping parameters can be defined as function of blade length, hence damping parameters can be different at root of tip of a blade.

Obl.	Command name	Explanation
*	nsec	Number of input lines
*	sec	This command must be repeated nsec times. 1. r/R. Non-dim distance from node 1 to node N. 2. k_x Stiffness proportional damping around x 3. k_y Stiffness proportional damping around y 4. k_z Stiffness proportional damping around z

9.2.4 Sub sub command – damping_posdef_distributed

In this command block, Rayleigh damping parameters can be defined as function of blade length, hence damping parameters can be different at root of tip of a blade.

Obl.	Command name	Explanation
*	nsec	Number of input lines
*	sec	This command must be repeated nsec times. 1. r/R. Non-dim distance from node 1 to node N. 2. k_x Stiffness proportional damping around x 3. k_y Stiffness proportional damping around y 4. k_z Stiffness proportional damping around z

9.2.5 Sub sub command – visualization_profile

This command block is used together with the command name visualization in the main command block simulation. Default profiles are:

- Blade: An aerodynamic profile where thickness <95%, otherwise a cylinder. Dimensions as specified in the aerodynamic blade layout file.

- Other bodies: Cylinder. The diameter is calculated from the mass and inertia specified in the structural data

Obl.	Command name	Explanation
*	type	Profile type. (options are: “cylinder”, “cube” and “blade”)
*	nsec	Number of visualization sections
*	sec	This command must be repeated nsec times. 1. Distance from root [m or % or any other unit of choice (scaled relative to the largest number)] 2. Diameter (cylinder), width (cube), chord (blade) [m] 3. (not needed for cylinder), height (cube) [m], thickness (blade) [%]

9.3 Sub command - orientation

In this command block the orientation (regarding position and rotation) of every main_body are specified.

9.3.1 Sub sub command - base

The orientation of a main_body to which all other bodies are linked – directly or indirectly.

Obl.	Command name	Explanation
*	mbdy (old command name body still usable)	1. Main_body name that is declared to be the base of all bodies (normally the tower or foundation)
*	inipos	Initial position in global coordinates. 1. x-pos [m] 2. y-pos [m] 3. z-pos [m]
♣	mbdy_eulerang (old command name body_eulerang still usable)	Command that can be repeated as many times as needed. All following rotation are given as a sequence of euler angle rotations. All angle can be filled in (rotation order x,y,z), but it is recommended only to give a value different from zero on one of the angles and reuse the command if several rotations are needed. 1. θ_x [deg] 2. θ_y [deg] 3. θ_z [deg]
♣	mbdy_eulerpar (old command name body_eulerpar still usable)	The rotation is given as euler parameters (quaternions) directly (global coo). 1. r_0 2. r_1 3. r_2 4. r_3
♣	mbdy_axisangle (old command name body_axisangle still usable)	Command that can be repeated as many times as needed. A version of the euler parameters where the input is a rotation vector and the rotation angle of this vector. 1. x-value 2. y-value 3. z-value 4. angle [deg]
	mbdy_ini_rotvec_d1	Initial rotation velocity of main body and all subsequent attached bodies. A rotation vector is set up and the size of vector (the rotational speed) is given. The coordinate system used is main_body coo. 1. x-value 2. y-value 3. z-value 4. Vector size (rotational speed [rad/s])

♣ One of these commands must be present.

9.3.2 Sub sub command - relative

This command block can be repeated as many times as needed. However the orientation of every main_body should be described.

Obl.	Command name	Explanation
*	mbdy1	1. Main_body name to which the next main_body is attached.

	(old command name body1 still usable)	2. Node number of body1 that is used for connection. ("last" can be specified which ensures that the last node on the main_body is used, and "0" (zero) refers to the origin of the main body coordinate system).
*	mbdy2 (old command name body2 still usable)	1. Main_body name of the main_body that is positioned in space by the relative command. 2. Node number of body2 that is used for connection. ("last" can be specified which ensures that the last node on the main_body is used, and "0" (zero) refers to the origin of the main body coordinate system).
♣	mbdy2_eulerang (old command name body2_eulerang still usable)	Command that can be repeated as many times as needed. All following rotation are given as a sequence of euler angle rotations. All angle can be filled in (rotation order x,y,z), but it is recommended only to give a value different from zero on one of the angles and reuse the command if several rotations are needed. Until a rotation command is specified body2 has same coo. as body1. Rotations are performed in the present body2 coo. system. 1. θ_x [deg] 2. θ_y [deg] 3. θ_z [deg]
♣	mbdy2_eulerpar (old command name body2_eulerpar still usable)	The rotation is given as euler parameters (quaternions) directly (global coo). 1. r_0 2. r_1 3. r_2 4. r_3
♣	mbdy2_axisangle (old command name body2_axisangle still usable)	Command that can be repeated as many times as needed. A version of the euler parameters where the input is a rotation vector and the rotation angle of this vector. Until a rotation command is specified main_body2 has same coo. as main_body1. Rotations are performed in the present main_body2 coo. system. 1. x-value 2. y-value 3. z-value 4. angle [deg]
	mbdy2_ini_rotvec_d1 (old command name body2_ini_rotvec_d1 still usable)	Initial rotation velocity of main body and all subsequent attached bodies. A rotation vector is set up and the size of vector (the rotational speed) is given. The coordinate system used is main_body2 coo. 1. x-value 2. y-value 3. z-value 4. Vector size (rotational speed [rad/s])

	relpos	Vector from coupling node of mbdy 1 to coupling node of mbdy 2 in mbdy1 coo system in case a certain distance between these nodes is required. (Default for overlapping coupling nodes, this vector is (0,0,0)) 1. x-value 2. y-value 3. z-value

9.4 Sub command - constraint

In this block constraints between the main_bodies and to the global coordinate system are defined.

9.4.1 Sub sub command – fix0

This constraint fix node number 1 of a given main_body to ground.

Obl.	Command name	Explanation
*	mbdy (old command name body still usable)	Name of main body that is fixed to ground at node 1
	disable_at	Time to which constraint can be disabled 1. t_0
	enable_at	Time to which constraint can be enabled 1. t_0

9.4.2 Sub sub command – fix1

This constraint fix a given node on one main_body to another main_body's node.

Obl.	Command name	Explanation
*	mbdy1 (old command name body1 still usable)	1. Main_body name to which the next main_body is fixed. 2. Node number of main_body1 that is used for the constraint. ("last" can be specified which ensures that the last node on the main_body is used, and "0" (zero) refers to the origin of the main body coordinate system).
*	mbdy2 (old command name body2 still usable)	1. Main_body name of the main_body that is fixed to main_body1. 2. Node number of main_body2 that is used for the constraint. ("last" can be specified which ensures that the last node on the main_body is used, and "0" (zero) refers to the origin of the main body coordinate system).
	disable_at	Time to which constraint can be disabled 1. t_0
	enable_at	Time to which constraint can be enabled 1. t_0

9.4.3 Sub sub command – fix2

This constraint fix a node 1 on a main_body to ground in x,y,z direction. The direction that is free or fixed is optional.

Obl.	Command name	Explanation
*	mbdy (old command name body still usable)	1. Main_body name to which node 1 is fixed.
*	dof	Direction in global coo that is fixed in translation 1. x-direction (0=free, 1=fixed) 2. y-direction (0=free, 1=fixed) 3. z-direction (0=free, 1=fixed)

9.4.4 Sub sub command – fix3

This constraint fix a node to ground in t_x,t_y,t_z rotation direction. The rotation direction that is free or fixed is optional.

Obl.	Command name	Explanation
*	mbdy (old command name body still usable)	1. Main_body name to which node 1 is fixed. 2. Node number
*	dof	Direction in global coo that is fixed in rotation 1. tx-rot.direction (0=free, 1=fixed) 2. ty-rot.direction (0=free, 1=fixed) 3. tz-rot.direction (0=free, 1=fixed)

9.4.5 Sub sub command – fix4

Constraint that locks a node on a body to another node in translation but not rotation with a pre-stress feature. The two nodes will start at the defined positions to begin with but narrow the distance until fully attached at time T.

Obl.	Command name	Explanation
*	mbdy1 (old command name body1 still usable)	1. Main_body name to which the next main_body is fixed. 2. Node number of main_body1 that is used for the constraint. (“last” can be specified which ensures that the last node on the main_body is used, and “0” (zero) refers to the origin of the main body coordinate system).
*	mbdy2 (old command name body2 still usable)	1. Main_body name of the main_body that is fixed to body1. 2. Node number of main_body2 that is used for the constraint. (“last” can be specified which ensures that the last node on the main_body is used, and “0” (zero) refers to the origin of the main body coordinate system).
	time	1. Time for the pre-stress process. Default=2sec
	disable_at	Time to which constraint can be disabled 1. t_0
	enable_at	Time to which constraint can be enabled 1. t_0

9.4.6 Sub sub command – bearing1

Constraint with properties as a bearing without friction. A sensor with same identification name as the constraint is set up for output purpose.

Obl.	Command name	Explanation
*	name	1. Identification name
*	mbdy1 (old command name body1 still usable)	1. Main_body name to which the next main_body is fixed with bearing1 properties. 2. Node number of main_body1 that is used for the constraint. ("last" can be specified which ensures that the last node on the main_body is used, and "0" (zero) refers to the origin of the main body coordinate system).
*	mbdy2 (old command name body2 still usable)	1. Main_body name of the main_body that is fixed to body1 with bearing1 properties. 2. Node number of main_body2 that is used for the constraint. ("last" can be specified which ensures that the last node on the main_body is used, and "0" (zero) refers to the origin of the main body coordinate system).
*	bearing_vector	Vector to which the free rotation is possible. The direction of this vector also defines the coo to which the output angle is defined. 1. Coo. system used for vector definition (0=global,1=mbdy1,2=mbdy2) 2. x-axis 3. y-axis 4. z-axis
	sensor_offset_deg	User defined initial bearing angle in degrees. Used for sensor (output). 1. θ_0 [deg]
	sensor_offset_rad	User defined initial bearing angle in radians. Used for sensor (output). 1. θ_0 [rad]
	disable_at	Time to which constraint can be disabled 1. t_0
	enable_at	Time to which constraint can be enabled 1. t_0

9.4.7 Sub sub command – bearing2

This constraint allows a rotation where the angle is directly specified by an external dll action command.

Obl.	Command name	Explanation
*	name	1. Identification name
*	mbdy1 (old command name body1 still usable)	1. Main_body name to which the next main_body is fixed with bearing2 properties. 2. Node number of main_body1 that is used for the constraint. ("last" can be specified which ensures that the last node on the main_body is used, and "0" (zero) refers to the origin of the main body coordinate system).
*	mbdy2 (old command name body2 still usable)	1. Main_body name of the main_body that is fixed to main_body1 with bearing1 properties. 2. Node number of main_body2 that is used for the constraint. ("last" can be specified which ensures that the last node on the main_body is used, and "0" (zero) refers to the origin of the main body coordinate system).
*	bearing_vector	Vector to which the rotation occur. The direction of this vector also defines the coo to which the output angle is defined. 1. Coo. system used for vector definition (0=global,1=mbdy1, 2=mbdy2) 2. x-axis 3. y-axis 4. z-axis
	sensor_offset_deg	User defined initial bearing angle in degrees. Used for sensor (output) and control (input). 1. θ_0 [deg]
	sensor_offset_rad	User defined initial bearing angle in radians. Used for sensor (output) and control (input). 1. θ_0 [rad]
	disable_at	Time to which constraint can be disabled 1. t_0
	enable_at	Time to which constraint can be enabled 1. t_0

9.4.8 Sub sub command – bearing3

This constraint allows a rotation where the angle velocity is kept constant throughout the simulation.

Obl.	Command name	Explanation
*	name	1. Identification name
*	mbdy1 (old command name body1 still usable)	1. Main_body name to which the next main_body is fixed with bearing3 properties. 2. Node number of main_body1 that is used for the constraint. ("last" can be specified which ensures that the last node on the main_body is used, and "0" (zero) refers to the origin of the main body coordinate system).
*	mbdy2 (old command name body2 still usable)	1. Main_body name of the main_body that is fixed to body1 with bearing3 properties. 2. Node number of main_body2 that is used for the constraint. ("last" can be specified which ensures that the last node on the main_body is used, and "0" (zero) refers to the origin of the main body coordinate system).
*	bearing_vector	Vector to which the rotation occur. The direction of this vector also defines the coo to which the output angle is defined. 1. Coo. system used for vector definition (0=global,1=body1,2=body2) 2. x-axis 3. y-axis 4. z-axis
*	omegas	1. Rotational speed [rad/sec]

9.4.9 Sub sub command – bearing4

This constraint is a cardan shaft constraint. Locked in relative translation. Locked in rotation around one vector and allows rotation about the two other directions.

Obl.	Command name	Explanation
*	name	1. Identification name
*	mbdy1 (old command name body1 still usable)	1. Main_body name to which the next main_body is fixed with bearing3 properties. 2. Node number of main_body1 that is used for the constraint. ("last" can be specified which ensures that the last node on the main_body is used, and "0" (zero) refers to the origin of the main body coordinate system).
*	mbdy2 (old command name body2 still usable)	1. Main_body name of the main_body that is fixed to body1 with bearing3 properties. 2. Node number of main_body2 that is used for the constraint. ("last" can be specified which ensures that the last node on the main_body is used, and "0" (zero) refers to the origin of the main body coordinate system).
*	bearing_vector	Vector to which the rotation is locked. The rotation angle and velocity can be outputted around the two perpendicular directions. 1. Coo. system used for vector definition (0=global,1=mbdy1, 2=mbdy2) 2. x-axis 3. y-axis 4. z-axis

9.4.10 Sub sub command – bearing5

This constraint is a spherical constraint. Locked in relative translation. Free in rotation around all three axis, but only sensor on the main rotation direction.

Obl.	Command name	Explanation
*	name	1. Identification name
*	mbdy1 (old command name body1 still usable)	1. Main_body name to which the next main_body is fixed with bearing3 properties. 2. Node number of main_body1 that is used for the constraint. ("last" can be specified which ensures that the last node on the main_body is used, and "0" (zero) refers to the origin of the main body coordinate system).
*	mbdy2 (old command name body2 still usable)	1. Main_body name of the main_body that is fixed to body1 with bearing3 properties. 2. Node number of main_body2 that is used for the constraint. ("last" can be specified which ensures that the last node on the main_body is used, and "0" (zero) refers to the origin of the main body coordinate system).
*	bearing_vector	Vector to which the rotation is locked. The rotation angle and velocity can be outputted around the two perpendicular directions. 1. Coo. system used for vector definition (0=global,1=mbdy1, 2=mbdy2) 2. x-axis 3. y-axis 4. z-axis

10 DLL control

This block contains the possible Dynamic Link Library formats accessible for the user. The DLL's are mainly used to control the turbine speed and pitch, but since the DLL format is very general, other use is possible too e.g. external loading of the turbine. Since the HAWC2 core has no information about external stiffness or inertia we have experienced some issues with the solver if the DLL includes high stiffness terms or especially large inertia terms. The new `type2_dll` interface is slightly more stable related to the solver than the `hawc_dll` interface.

10.1 Main command block – dll

There are two DLL mechanisms available: `hawc_dll` and `type2_dll`. Both have two different interfaces (as documented in more detailed in the following sections 10.3 and 10.4) and have one other important distinction: a `hawc_dll` is updated in each aero-structure iteration, i.e. typically multiple times per time step while the `type2_dll` is only updated once per time step.

10.2 Important note about DLL file names

For both DLL interfaces the user needs to refer to the location of the specific DLL in use. Since version 12.9 HAWC2 is available for 3 different architectures (Windows 32-bit, Windows 64-bit and Linux 64-bit). To facilitate easy use of the same htc file across the different architectures, the intention is that with a single htc input file a user should be able to run on win32, win64 and linux without modifications. To this end, HAWC2 is using the following strategy:

- Determine what file name extension to use:
  - Win32: `.dll`
  - Win64: `_64.dll` (recommended), `.dll`
  - Linux: `.so`
- Find the correct path of the dll:
  - Absolute path (if the absolute path is specified)
  - Relative path relative to:
    - Current working directory (cwd)
    - The location of the HAWC2 executable
- On Linux, paths and file names are case sensitive (in contrast to Windows). Functionality to mimic the Windows behaviour on Linux has therefore been added. This functionality tries the following:
  - Load the exact specified filename (Note the automatic convertion to lower case and the exceptions described below)
  - Find the first filename that case-insentively matches the specified filename. This is done using `find /my/dir -maxdepth 1 -type f -ipath '*my_dll_name.so'`.
    Note: "first" may be arbitrary. Hence, avoid to have multiple files with the same name except for their case (e.g. `my_hawc2_dll.so` and `My_HAWC2_dll.so`) in the same folder.
    Note: With thousands of parallel simulations this behaviour may be problematic for the file system. Every use of `find`-command is therefore printed to the log file and in case the usage can be avoided by specifying the correct case-sensitive filename a warning is printed too.
- All input in the htc file(s) are converted to lower case with the following exceptions:
  - single-quoted strings, e.g. `'dont_CHANGE_case.dll'`

- htc lines starting with `filename`
- htc lines starting with `continue_in_file`

- Note that the log file will always report which files have been loaded so in case of doubt inspect that.

Each DLL needs to be compiled for each of the three different platforms independently, but with this functionality, the same input htc file, e.g.

```
...
begin dll;
  begin type2_dll;
    name 'MyDLL';
    filename  ./my_folder/MyDLL.dll ;
    ...
  end type2_dll;
end dll;
...
```

will load and use the correct dll on all platforms if the three files, `MyDLL.dll` (win32 compilation), `MyDLL_64.dll` (win64 compilation) and `MyDLL.so` (linux compilation) is put in `my_folder`.

10.3 Sub command block – `hawc_dll`

In the `hawc_dll` format a subroutine within an externally written DLL is setup. In this subroutine call two one-dimensional arrays are transferred between the HAWC2 core and the DLL procedure. The first contains data going from the HAWC2 core to the DLL and the other contains data going from the DLL to the core. It is very important to notice that the data is transferred between HAWC2 and the DLL in every time step and every iteration. The user should handle the iteration inside the DLL.

Two more subroutines are called if they are present inside the dll file:

The first is an initialisation call including a text string written in the init_string in the commands below. This could be the name of a file holding local input parameters to the data transfer subroutine. This call is only performed once. The name of this subroutine is the same name as the data transfer subroutine defined with the command dll_subroutine below with the extra name '_init', hence is the data transfer subroutine is called 'test', the initialisation subroutine will be 'test_init'.

The second subroutine is a message exchange subroutine, where messages written in the DLL can be send to the HAWC2 core for logfile writing. The name of this subroutine is the same name as the data transfer subroutine defined with the command dll_subroutine below with the extra name '_message', hence is the data transfer subroutine is called 'test', the initialisation subroutine will be 'test_message'.

The command block can be repeated as many times as desired. Reference number to DLL is same order as listed, starting with number 1. However it is recommended to refer the DLL using the name feature which in many cases can avoid confusion.

Obl.	Command name	Explanation
	name	1. Reference name of this DLL (to be used with DLL output commands)
*	filename	1. Filename incl. relative path of the DLL (example ./DLL/control.dll)
*	dll_subroutine	1. Name of subroutine in DLL that is addressed (remember to specify the name in the DLL with small letters!)
*	arraysizes	1. size of array with outgoing data 2. size of array with ingoing data
	deltat	1. Time between dll calls. Must correspond to the simulation sample frequency or be a multiple of the time step size. If deltat=0.0 or the deltat command line is omitted the HAWC2 code calls the dll subroutine at every time step.
	init_string	1. Text string (max 256 characters) that will be transferred to the DLL through the subroutine 'subroutine_init'. Subroutine is the name given in in the command dll_subroutine. No blanks can be included.

10.4 Sub command block – `type2_dll`

This dll interface is an updated slightly modified version of the `hawc_dll` interface. In the `type2_dll` format a subroutine within an externally written DLL is setup. In this subroutine call two one-dimensional arrays are transferred between the HAWC2 core and the DLL procedure. The first contains data going from the HAWC2 core to the DLL and the other contains data going from the DLL to the core. It is very important to notice that the data are transferred between HAWC2 and the DLL in the first call of every time step where the out-going variables are based on last iterated values from previous time step. The sub command output and actions are identical for both the `hawc_dll` and the `type2_dll` interfaces.

In the dll connected with using the `type2_dll` interface two subroutines should be present. An initialization routine called only once before the time simulation begins, and an update routine called in every time step. The format in the calling of these two subroutines are identical where two arrays of double precision is exchanged. The subroutine uses the cdecl calling convention.

Obl.	Command name	Explanation
	name	1. Reference name of this DLL (to be used with DLL output commands)
*	filename	1. Filename incl. relative path of the DLL (example ./DLL/control.dll)
*	dll_subroutine_init	1. Name of initialization subroutine in DLL that is addressed (remember to specify the name in the DLL with small letters!)
*	dll_subroutine_update	1. Name of subroutine in DLL that is addressed at every time step (remember to specify the name in the DLL with small letters!)
	init_string	1. String that HAWC2 will pass to a subroutine named `initstring` before calling the initialization one.
*	arraysizes_init	1. size of array with outgoing data in the initialization call 2. size of array with ingoing data in the initialization call
*	arraysizes_update	1. size of array with outgoing data in the update call 2. size of array with ingoing data in the update call
	deltat	1. Time between dll calls. Must correspond to the simulation sample frequency or be a multiple of the time step size. If deltat=0.0 or the deltat command line is omitted the HAWC2 code calls the dll subroutine at every time step.

when using the `type2_dll` interface the values transferred to the DLL in the initialization phase is done using a sub command block called init. The commands for this subcommand block is identical to the output subcommand explained below, but only has the option of having the constant output sensor available. An example is given for a small dll that is used for converting rotational speed between high speed and low speed side of a gearbox:

```
begin dll;
  begin type2_dll;
    name hss_convert;
    filename  ./control/hss_convert.dll ;
    arraysizes_init  3 1 ;
    arraysizes_update  2 2 ;
    begin init;
      constant 1 2.0 ;     number of used sensors - in this case only 1
      constant 2 35.110;   gearbox ratio
      constant 3 35.110;   gearbox ratio
    end init;
    begin output;
      constraint bearing1 shaft_rot 2 only 2 ;   rotor speed in rpm
      constraint bearing1 shaft_rot 3 only 2 ;   rotor speed in rad/s
    end output;
;
    begin actions;
;      rotor speed in rpm * gear_ratio
;      rotor speed in rad/s * gear_ratio
    end actions;
  end type2_dll;
end dll;
```

10.5 Sub command block - init

In this block `type2_dll`s can be initialized by passing constants to specific channels.

Obl.	Command name	Explanation
*	constant	Constants passed to the dll. 1. Channel number 2. Constant value

10.6 Sub command block – output

In this block the same sensors are available as when data results are written to a file with the main block command output, see section 17. The order of the sensors in the data array is continuously increased as more sensors are added.

10.7 Sub command block – actions

In this command block variables inside the HAWC2 code is changed depending of the specifications. This command block can be used for the `hawc_dll` interface as well as the `type2_dll` interface. An action commands creates a handle to the HAWC2 model to which a variable in the input array from the DLL is linked.

!NB in the command name two separate words are present.

Obl.	Command name	Explanation
	aero beta	The flap angle beta is set for a trailing edge flap section (is the mhhmagf stall model is used). The angle is positive towards the pressure side of the profile. Unit is [deg] 1. Blade number 2. Flap section number
	aero bem_grid_a	1. Number of points
	body force_ext	An external force is placed on the structure. Unit is [N]. 1. body name 2. node number 3. componet (1 = F_x, 2 = F_y, 3 = F_z)
	body moment_ext	An external moment is placed on the structure. Unit is [Nm]. 1. body name 2. node number 3. component (1 = M_x, 2 = M_y, 3 = M_z)
	body force_int	An external force with a reaction component is placed on the structure. Unit is [N]. 1. body name for action force 2. node number 3. component (1 = F_x, 2 = F_y, 3 = F_z) 4. body name for reaction force 5. Node number
	body moment_int	An external moment with a reaction component is placed on the structure. Unit is [N]. 1. body name for action moment 2. node number 3. component (1 = M_x, 2 = M_y, 3 = M_z) 4. body name for reaction moment 5. Node number
	body bearing_angle	A bearing either defined through the new structure format through bearing2 or through the old structure format (spitch1=pitch angle for blade 1, spitch2=pitch angle for blade 2,...). The angle limits are so far [0-90deg].

		1. Bearing name
	mbdy force_ext	An external force is placed on the structure. Unit is [N]. 1. main body name 2. node number on main body 3. component (1 = F_x, 2 = F_y, 3 = F_z), if negative number the force is inserted with opposite sign. 4. coordinate system (possible options are: mbdy name, ”global”, ”local”). “local” means local element coo on the inner element (on the element indexed 1 lower that the node number). One exception if node number =1 then the element nr. also equals 1.
	mbdy moment_ext	An external moment is placed on the structure. Unit is [Nm]. 1. main body name 2. node number on main body 3. component (1 = M_x, 2 = M_y, 3 = M_z), if negative number the moment is inserted with opposite sign. 4. coordinate system (possible options are: mbdy name,”global”,”local”). “local” means local element coo on the inner element (on the element indexed 1 lower that the node number). One exception if node number =1 then the element nr. also equals 1.
	mbdy force_int	An internal force with a reaction component is placed on the structure. Unit is [N]. 1. main body name for action force 2. node number on main body 3. component (1 = F_x, 2 = F_y, 3 = F_z), if negative number the force is inserted with opposite sign. 4. coordinate system (possible options are: mbdy name, ”global”, ”local”). “local” means local element coo on the inner element (on the element indexed 1 lower that the node number). One exception if node number =1 then the element nr. also equals 1. 5. main body name for reaction force 6. Node number on this main body
	mbdy moment_int	An internal force with a reaction component is placed on the structure. Unit is [Nm]. 1. main body name for action moment 2. node number on main body 3. component (1 = M_x, 2 = M_y, 3 = M_z), if negative number the moment is inserted with opposite sign. 4. coordinate system (possible options are: mbdy name,”global”,”local”). “local” means local element coo on the inner element (on the element indexed 1 lower that the node number). One exception if node number =1 then the element nr. also equals 1. 5. main body name for reaction moment 6. Node number on this main body
	constraint bearing2 angle_deg	The angle of a bearing2 constraint is set. The angle limits are so far [± 90 deg]. 1. Bearing name
	constraint bearing3 angle_deg	The angle of a bearing3 constraint is set. The angle limits are so far [± 90 deg]. 1. Bearing name

	constraint bearing3 omegas	The angular velocity of a bearing3 constraint is set. 1. Bearing name
	body printvar	Variable is just echoed on the screen. No parameters.
	body ignore	1. Number of consecutive array spaces that will be ignored
	mbdy printvar	Variable is just echoed on the screen. No parameters.
	mbdy ignore	1. Number of consecutive array spaces that will be ignored
	general printvar	Variable is just echoed on the screen. No parameters.
	general ignore	1. Number of consecutive array spaces that will be ignored
	general stop_simulation	Logical switch. If value is 1 the simulation will be stopped and output written.
	wind printvar	Variable is just echoed on the screen. No parameters.
	wind windspeed_u	External contribution to wind speed in u-direction [m/s]
	wind winddir	External contribution to the wind direction (turb. box is also rotated) [deg]
	quake comp	1. Degree of freedom
	ext_sys control	1. Name of external system

10.8 hawc_dll format example written in FORTRAN 90

```fortran
subroutine test(n1,array1,n2,array2)
implicit none
!DEC$ ATTRIBUTES DLLEXPORT, ALIAS:'test'::test
integer*4           :: n1, &    ! Dummy integer value containing the array size of array1
                       n2       ! Dummy integer value containing the array size of array2
real*4,dimension(10) :: array1  ! fixed-length array, data from HAWC2 to DLL
                                ! - in this case with length 10
real*4,dimension(5)  :: array2  ! fixed-length array, data from DLL to HAWC2
                                ! - in this case with length 5

! Code is written here

end subroutine test

!-------------------------------------------------------

Subroutine test_init(string256)
Implicit none
!DEC$ ATTRIBUTES DLLEXPORT, ALIAS:'test_init'::test_init
Character*256 :: string256

! Code is written here

End subroutine test_init

!-------------------------------------------------------

Subroutine test_message(string256)
Implicit none
!DEC$ ATTRIBUTES DLLEXPORT, ALIAS:'test_message'::test_message
Character*256 :: string256

! Code is written here

End subroutine test_message
```

10.9 hawc_dll format example written in Delphi / Lazarus / Pascal

```
library test_dll;

type
  array_10 = array[1..10] of single;
  array_5  = array[1..5] of single;
  ts       = array[0..255] of char;

Procedure test(var n1:integer;var array1 : array_10;
               var n2:integer;var array2 : array_5);stdcall;
// n1 is a dummy integer value containing the size of array1
// n2 is a dummy integer value containing the size of array2
begin
  // Code is written here

end;

//----------------------------------------------------------

Procedure test_init(var string256:ts; length:integer);stdcall;
var
  init_str:string[255]
begin
  init_str=strpas(string256);
  // Code is written here
  writeln(init_str);
end;

//----------------------------------------------------------

Procedure test_message(var string256:ts; length:integer);stdcall;
var
  message_str:string;
begin
  // Code is written here
  message_str:='''This is a test message';
  strPCopy(string256,message_str);
end;

exports test,test_init,test_message;

begin
  writeln('The DLL pitchservo.dll is loaded with succes');

  // Initialization of variables can be performed here
end;

end.
```

10.10 hawc_dll format example written in C

```c
extern "C" void __declspec(dllexport) __stdcall test(int size_of_Data_in,
float Data_in[], int size_of_Data_out, float Data_out[])
{
 for (int i=0; i<size_of_Data_out; i++) Data_out[i]=0.0;
//
 printf("size_of_Data_in  %d: \n",size_of_Data_in);
 printf("Data_in          %g: \n",Data_in[0]);
 printf("size_of_Data_out %d: \n",size_of_Data_out);
 printf("Data_out         %g: \n",Data_out[0]);

}

extern "C" void __declspec(dllexport) __stdcall test_init(char* pString, int length)
{
        // Define buffer (make room for NULL-char)
        const int max_length = 256;
        char buffer[max_length+1];
        //
        // Print the length of pString
        printf("test_init::length = %d\n",length);
        //
        // Transfer string
        int nchar = min(max_length, length);
        memcpy(buffer, pString, nchar);
        //
        // Add NULL-char
        buffer[nchar] = '\0';
        //
        // Print it...
        printf("%s\n",buffer);
}

extern "C" void __declspec(dllexport) __stdcall test_message(char* pString, int
    max_length)
{
        // test message (larger than max_length)
        char pmessage[] = "This is a test message "
                         "and it continues and it continues and it continues "
                         "and it continues and it continues and it continues "
                         "and it continues and it continues and it continues "
                         "and it continues and it continues and it continues "
                         "and it continues and it continues and it continues "
                         "and it continues and it continues and it continues ";

        // Check max length  -  transfer only up to max_length number of chars
        int nchar = min((size_t)max_length, strlen(pmessage));  // nof chars to transfer
    // (<= max_length)
        memcpy(pString, pmessage, nchar);
        //
        // Add NULL-char if string space allows it (FORTRAN interprets a NULL-char as
// the end of the string)
        if (nchar < max_length) pString[nchar] = '\0';
}
```

10.11 type2_dll written in Delphi / Lazarus / Delphi

```
library hss_convert;

uses
  SysUtils,
  Classes,
  Dialogs;

Type
  array_1000 = array[0..999] of double;
Var
  factor : array of double;
  nr : integer;
{$R *.res}

procedure initialize(var InputSignals: array_1000;var OutputSignals: array_1000); cdecl;
var
  i : integer;
begin
  nr:=trunc(inputsignals[0]);
  if nr>0 then begin
    setlength(factor,nr);
    for i:=1 to nr do
      factor[i-1]:=Inputsignals[i];
    outputsignals[0]:=1.0;
  end else outputsignals[0]:=0.0;
end;

procedure update(var InputSignals: array_1000;var OutputSignals: array_1000); cdecl;
var
  i : integer;
begin
  for i:=0 to nr-1 do begin
    OutputSignals[i] := InputSignals[i]*factor[i];
  end;
end;

exports Initialize,Update;

begin
  // Main body

end.
```

10.12 type2_dll written in C

```c
#include <stdio.h>

void __declspec(dllexport) __cdecl initialize(double * Data_in, double * Data_out)
{
        for (int i = 0; i < 2; i++) {
                Data_out[i] = Data_in[i] * 2 + i;
                printf("INIT \n");
                printf("Data_in: %f \n", Data_in[i]);
                printf("Data out: %f \n", Data_out[i]);
        }
}
void __declspec(dllexport) __cdecl update(double * Data_in, double * Data_out)
{
        for (int i = 0; i < 2; i++) {
                Data_out[i] = Data_in[i] * 2 + i;
                printf("Update\n");
                printf("Data_in: %f \n", Data_in[i]);
                printf("Data out: %f \n", Data_out[i]);
        }
}
void __declspec(dllexport) __cdecl get_version(char * version)
{
        printf("Empty HAWC2 Controller (ver. 0.1)\n");
}
void __declspec(dllexport) __cdecl message(char * message)
{
        printf("Message\n");
}
void __declspec(dllexport) __cdecl initstring(char* str)
{
        printf("%s\n", str);
}
```

The compile command on Windows for the example above example is given below, for GCC and Intel c classic respectively:

```
gcc .\source.c -o ExampleHAWCController.dll -shared
```

```
icl .\source.c /LD /FeExampleHAWCController.dll
```

The compile command for Linux systems is given below, for GCC and Intel c classic. It should be noted that there may be missing dependencies if the compiler used to build the controller is not installed on the system which is running. This is known to happen on Linux systems for GCC.

```
gcc ./source.c -o ./ExampleHAWCController.so -shared -fPIC
```

```
icx ./source.c -o ./ExampleHAWCController.so -shared -fPIC
```

10.13 type2_dll format example written in FORTRAN 90

```fortran
subroutine update(array1,array2) bind(C, name="update")
implicit none
!DEC$ ATTRIBUTES DLLEXPORT :: update
!gcc$ attributes DLLEXPORT :: update
!gcc$ attributes cdecl :: update
real*8,dimension(2) :: array1 ! fixed-length array, data from HAWC2 to DLL
!  in this case with length 2
real*8,dimension(2) :: array2 ! fixed-length array, data from DLL to HAWC2
! in this case with length 2
! Code is written here
print *, "Update", array1(1)
end subroutine update
!-------------------------------------------------------
 Subroutine initialize(array1,array2) bind(C, name="initialize")
 use iso_c_binding, only: C_CHAR
 Implicit none
 !DEC$ ATTRIBUTES DLLEXPORT :: initialize
 !gcc$ attributes DLLEXPORT :: initialize
 !gcc$ attributes cdecl :: initialize
 real*8,dimension(2) :: array1 ! fixed-length array, data from HAWC2 to DLL
 ! in this case with length 2
 real*8,dimension(2) :: array2 ! fixed-length array, data from DLL to HAWC2
 ! in this case with length 2
 ! Code is written here
 print *, "Initialize", array1(1)
  End subroutine initialize
!-------------------------------------------------------
 Subroutine message(string256) bind(C, name="message")
 use iso_c_binding, only: C_CHAR
 Implicit none
 !DEC$ ATTRIBUTES DLLEXPORT :: message
 !gcc$ attributes DLLEXPORT :: message
 !gcc$ attributes cdecl :: message
 character(len=256) :: s
 Character(kind=C_CHAR) :: string256(256)
 integer :: i
 ! Code is written here
 s = "Message from controller DLL"
 ! copy to C character arrya
 do i=1,256
   string256(i) = s(i:i)
 enddo
 End subroutine message

 !-------------------------------------------------------
 Subroutine get_version(string256) bind(C, name="get_version")
 use iso_c_binding, only: C_CHAR
 Implicit none
 !DEC$ ATTRIBUTES DLLEXPORT :: get_version
 !gcc$ attributes DLLEXPORT :: get_version
 !gcc$ attributes CDECL :: get_version
 Character(kind=C_CHAR) :: string256(256)
 ! Code is written here
 string256(1:3) = (/"0",".","1"/)
 End subroutine get_version

 !-------------------------------------------------------
 Subroutine initstring(istring) bind(C, name='initstring')
 !DEC$ ATTRIBUTES DLLEXPORT :: initstring
 use iso_c_binding, only: C_CHAR
 Implicit none

 !! Print a string before the initialization.
```

```fortran

integer(kind=1), dimension(*), intent(in) :: istring
  !! Input from HAWC2.
  !! The string is passed in decimal format.
  !! This is how the interface is defined in HAWC2 and must not be changed.

character(kind=C_CHAR, len=1), dimension(256) :: char_array
  !! The whole string from HAWC2, converted to character array.
character(kind=C_CHAR, len=256) :: string
  !! The whole string from HAWC2, converted to string.

! Convert decimal to character array.
char_array = char(istring(1:256))
! Convert character array to string.
string = transfer(char_array, string)
! Print the initialization string.
write(*, '(A)') string
end Subroutine initstring
```

The compile command for the example above example is given below, for GCC and intel fortran classic respectively:

```
gfortran .\source.f90 \
-o .\ExampleHAWCController.dll -shared -cpp -fno-underscoring

ifort .\source.f90 /FeExampleHAWCController.dll /fpp /dll
```

The compile command for Linux systems is given below, for GCC and Intel c classic. It should be noted that there may be missing dependencies if the compiler used to build the controller is not installed on the system which is running. This is known to happen on Linux systems for GCC.

```
gfortran ./source.f90 -o ./ExampleHAWCController.so -shared -fPIC -cpp

ifort ./source.f90 -o ExampleHAWCController.so -shared -fPIC -fpp
```

In order to import the controller into HAWC2, the two sections should be added to the .htc file. A section similar to the one directly below should be added in the dll section of the htc file.

```
begin type2_dll;
  name empty_hawc_controller ;
  filename  ./PATH/TO/THE/CUSTOM/CONTROLLER.dll;
;
  dll_subroutine_init initialize ;
  dll_subroutine_update update ;
;
  arraysizes_init 2 2 ;
  arraysizes_update 2 2 ;
  begin init ;
    constant 1 2.3;
    constant 2 3;
  end init ;
;
  begin output ;
    general time;
    general time;
  end output;
end type2_dll;
```

Additionally, lines should be added in the output section specifying what data from the interface between the controller and HAWC2 is to be saved in the output file. Details on this can be found the the Output chapter (Chapter 17) of the manual.

```
  dll inpvec 6 1 # Data into the controller;
  dll outvec 6 1 # Data out of the controller;
```

11 Wind and Turbulence

11.1 Main command block -wind

Obl.	Command name	Explanation
*	wsp	1. Mean wind speed in center [m/s]
*	density	1. Density of the wind [kg/m3]
*	tint	Turbulence intensity [-].
*	horizontal_input	This command determines whether the commands above should be understood as defined in the global coordinate system (with horizontal axes) or the meteorological coordinates system (u,v,w) witch can be tilted etc. 1. (0=meteorological, 1=horizontal)
*	center_pos0	Global coordinates for the center start point of the turbulence box, meteorological coordinate system etc. (default should the hub center) 1. x_G [m] 2. y_G [m] 3. z_G [m]
*	windfield_rotations	Orientation of the wind field. The rotations of the field are performed as a series of 3 rotations in the order yaw, tilt and roll. When all angles are zero the flow direction is identical to the global y direction. 1. Wind yaw angle [deg], positive if the wind comes from the right side when sitting in the nacelle and looking upwind (i.e. in the -y_G direction). 2. Terrain slope angle [deg], positive when the wind comes from below. 3. Roll of wind field [deg], positive when the wind field is rotated according to the turbulence u-component.
*	shear_format	Definition of the mean wind shear 1. Shear type 0=none. !This option sets the mean wind speed to zero ! $\bar{u}(z) = 0$ 1=constant $\bar{u}(z)$ = wsp. The value is taken from the `wsp` parameter. 2=logarithmic $$\bar{u}(z) = u_0 \frac{\log \frac{-z_0^G + z^M}{r_0}}{\log \frac{-z_0^G}{r_0}}$$ 3=power law $$\bar{u}(z) = u_0 \left(\frac{-z_0^G + z^M}{-z_0^G} \right)^\alpha$$ 4=linear $$\bar{u}(z) = u_0 \frac{\partial u}{\partial z}$$ 2. Parameter used together with shear type (case of shear type: 0=dummy, 1=dummy, 2=r_0, 3= a, 4=d_u/d_z at center)
*	turb_format	1. Turbulence format (0=none, 1=mann, 2=flex)

Obl.	Command name	Explanation
*	tower_shadow_method	1. Tower shadow model (0=none, 1=potential flow – default, 2=jet model, 3=potential_2 (flow where shadow source is moved and rotated with tower coordinates system), 4=jet_2 (jet where shadow source is moved and rotated with tower coordinates system). Please see sections 11.12 to 11.15 for sub block commands.
	scale_time_start	1. Starting time for turbulence scaling [s]. Stop time is determined by simulation length.
	wind_ramp_factor	Command that can be repeated as many times as needed. The wind_ramp_factor is used to calculate a factor that is multiplied to the wind speed vectors. Can be used to make troublefree cut-in situations. Linear interpolation is performed between t_0 and t_{stop}. 1. time start, t_0 2. time stop, t_{stop} 3. factor at t_0 4. factor at t_{stop}
	wind_ramp_abs	Command that can be repeated as many times as needed. The wind_ramp_abs is used to calculate a wind speed that is added to the wind speed u-component. Can be used to make wind steps etc. Linear interpolation is performed between t_0 and t_{stop}. 1. time start, t_0 2. time stop, t_{stop} 3. wind speed at t_0 4. wind speed at t_{stop}
	user_defined_shear	1. Filename incl. relative path to file containing user defined shear factors (example ./data/shear.dat)
	user_defined_-shear_turbulence	1. Filename incl. relative path to file containing user defined shear turbulence factors (example ./data/shearturb.dat)
	met_mast_wind	1. Filename incl. relative path to file containing time series of wind components in meteorological coordinates. This command is deprecated see section 11.8
	iec_gust	Gust generator according to IEC 61400-1 1. Gust type 'eog' = extreme operating gust $u(z,t) = u(z,t) - 0.37A \sin\left(\frac{3\pi(t-t_0)}{T}\right)\left(1 - \cos\frac{2\pi(t-t_0)}{T}\right)$ 'edc' = extreme direction change $\theta(t) = 0.5\phi_0\left(1 - \cos\left(\frac{\pi(t-t_0)}{T}\right)\right)$ 'ecg' = extreme coherent gust $u(z,t) = u(z,t) + 0.5A\left(1 - \cos\left(\frac{\pi(t-t_0)}{T}\right)\right)$ 'ecd' = extreme coherent gust with dir. change $u(z,t) = u(z,t) + 0.5A\left(1 - \cos\left(\frac{\pi(t-t_0)}{T}\right)\right)$ $\theta(t) = 0.5\phi_0\left(1 - \cos\left(\frac{\pi(t-t_0)}{T}\right)\right)$

Obl.	Command name	Explanation
		'ews' = extreme wind shear $$vw_{res} = \sqrt{y_M^2 + z_M^2}$$ $$u(z,t) = u(z,t) + vw_{res}\, A\left(1 - \cos\left(\frac{2\pi(t-t_0)}{T}\right)\right)$$ $$* \cos\left(\text{atan2}\left(y^M, -z^M\right) - \phi_0\right)$$ even though the 'ews' expressions do not match the expressions in the standard completely, it gives identical results provided a mutual power law shear is used and the A parameter is set to $$A = \frac{2.5 + 0.2\beta\sigma_1\left(\frac{D}{\Lambda_1}\right)^{\frac{1}{4}}}{D}$$ and the parameter φ_0 is set to 0, 90, 180, 270 [deg] respectively. Note that: • Y_M and Z_M refer to the horizontal and vertical wind speeds respectively (expressed in meteorological coordinates, or V_M and W_M in figure 1). • D refers to the rotor diameter. 2. Amplitude A [m/s]. For the 'eog', 'edc', 'ecd' this corresponds to the parameter 'V_{gust}', '0', 'V_{cg}' respectively, in the IEC61400-1 standard. 3. Angle φ_0 [deg] 4. Time start, t_0 [s] 5. Duration T [s]

11.2 Sub command block - mann

Block that must be included if the mann turbulence format is chosen. Normal practice is to use all three turbulence components (u,v,w) but only the specified components are used. In 2008 the turbulence generator was linked to the code so mannturbulence can be created without using external software. The command create_turb_parameters will search for turbulence files with names given below, but if these are not found the turbulence will be created.

A short explanation of the parameters L and $\alpha\varepsilon^{\frac{2}{3}}$ and its relation to the IEC61400-1 ed. 3 standard is given:

The fundamentals of the Mann model is isotropic turbulence in neutral atmospheric conditions. The energy spectrum is given based on the Von Karman spectrum (1). In isotropic turbulence, the properties of turbulence like variance and turbulent length scale is identical for all three direction corresponding to vortex structures being circular.

$$E(k) = \alpha\varepsilon^{\frac{2}{3}} L^{\frac{5}{3}} \frac{(Lk)^4}{\left(1 + (Lk)^2\right)^{\frac{17}{6}}} \tag{1}$$

The relation between wave number k and frequency f is related through the mean wind speed $\bar{U}$.

$$k = \frac{2\pi f}{\bar{U}} \tag{2}$$

However, atmospheric conditions are not isotropic and the vortex structures become more elliptic in shape with longer length scale and higher variance level in the u direction. In the

Mann model, this is accounted for using rapid distortion theory quantified through a shear blocking factor Γ. A Γ parameter of 0 corresponds to isotropic turbulence, whereas a higher Γ value is used for non-isotropic turbulence. The relation between non-isotropic and isotropic properties as function of Γ can be seen in Figure 5. For neutral atmospheric conditions (often referred to as "normal" conditions) it is recommended to use $\Gamma = 3.9$ in combination with a length scale of $L = 0.8\Lambda_1$. Λ_1 is defined as the wavelength where the longitudinal power spectral density is equal to 0.05. According to the IEC61400-1 the wavelength Λ_1 shall be considered as a constant of 42m above a height of 60m, or $0.7z$ otherwise (z being the height). In the Mann generation of turbulence a length scale L has to be used. This is the length scale of the Von Karman spectrum (1) and therefore different than the length scale used in the Kaimal formulation (3). The energy spectrum of Kaimal is formulated

$$E(f) = \sigma^2 \frac{4L/\bar{U}}{\left(1 + 6fL/\bar{U}\right)^{\frac{5}{3}}} \tag{3}$$

where the input parameters are given based on the table values in

	Velocity component index (k)		
	1	2	3
Standard deviation σ_k	σ_1	0,8 σ_1	0,5 σ_1
Integral scale, L_k	8,1 Λ_1	2,7 Λ_1	0,66 Λ_1

Figure 4: Information about Kaimal length scales and standard deviation ratio from the IEC61400-1

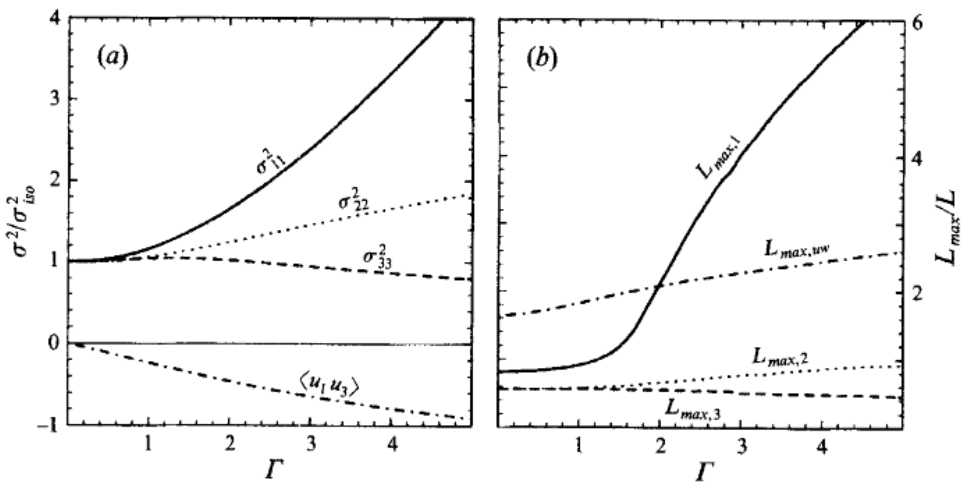


Figure 5: Turbulence characteristics compared to isotropic conditions as function of gamma parameter, Mann.. Left: Relation between variance is changed for higher shear distortions. Right: The relation between length scales are also changed for non-isotropic turbulence. It is recommended to use Γ = 3.9 for normal atmospheric conditions. This is also the requirement in the IEC61400-1 standard. Isotropic conditions are obtained using Γ=0.

The result of using $\Gamma = 3.9$ is that the structure of the turbulence corresponds to the normal atmospheric conditions, but the actual level of turbulence is also affected as seen in Figure 4. It is not straight forward to give the exact analytical relationship between the input parameter $\alpha\varepsilon^{\frac{2}{3}}$ and the final longitudinal variance and it is therefore very practical to introduce a turbulence scaling factor SF. This turbulence scaling factor is calculated based on the actual variance level in the box (normally extracted in the center of the box of longitudinal turbulence) and the target variance σ^2_{target} based on the requested turbulence intensity $\sigma = Ti\,\bar{U}$. In this case of rescaling, which is the normal usage, the input value for $\alpha\varepsilon^{\frac{2}{3}}$ can be any arbitrary value except for zero.

$$SF = \sqrt{\frac{\sigma^2_{\text{target}}}{\sigma^2}} \tag{4}$$

The scale factor is to be multiplied to every values in the turbulence box for all the u,v and w directions. This is done automatically inside HAWC2.

11.2.1 Mann turbulence format

The mann turbulence binary format consist of one file per turbulence component, u,v,w. Each file contains turbulence values stored as 32-bit floats (little endian). It can be read from python using:

```python
import numpy as np
u = np.fromfile(u_filename, dtype=np.float32).reshape(Nx,Ny,Nz)
```

Turbulence direction:

- Wrong direction (default in HAWC2 ≤ 13.0): First plane in file, `u[0,:,:]`, is box front.
- Correct direction (default in HAWC2>13.0): Last plane, `u[-1,:,:]` is box front.

The turbulence coordinate system and advection direction is detailed and illustrated in the table below, and in figure 6 respectively. The coordinates given here assumes indexing starting at 0.

Location in file	Box (x,y,z)
0	(0,0,0)
1	(0,0,1)
Nz-1	(0,0,-1)
Nz	(0,1,0)
Nz+1	(0,1,1)
Ny*Nz-1	(0,-1,-1)
Ny*Nz	(1,0,0)

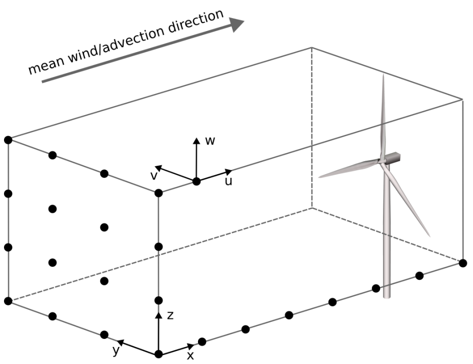


Figure 6: Illustration of the Mann turbulence coordinate system and advection direction.

Obl.	Command name	Explanation
	create_turb_parameters	With this command, the code will search for turbulence files with names given below, but if these are not found the turbulence will be created based on the given parameters. 1. Length scale L (L=33.6 according to the IEC standard at 42m and above) 2. $\alpha\varepsilon^{2/3}$ (when rescaling applied, 1.0 is normal practice) 3. γ (3.9 for neutral atmospheric conditions) 4. Seed number (any integer will do) 5. High frequency compensation (1=point velocity only represent local value which is closest to anemometer measurements, recommended in most cases, 0=point velocity represents average velocity in grid volume)

Obl.	Command name	Explanation
	filename_u	1. Filename incl. relative path to file containing mann turbulence u-component (example ./turb/mann-u.bin)
	filename_v	1. Filename incl. relative path to file containing mann turbulence v-component (example ./turb/mann-v.bin)
	filename_w	1. Filename incl. relative path to file containing mann turbulence w-component (example ./turb/mann-w.bin)
*	box_dim_u	1. Number of grid points in u-direction 2. Length between grid points in u-direction [m]
*	box_dim_v	1. Number of grid points in v-direction 2. Length between grid points in v-direction [m]
*	box_dim_w	1. Number of grid points in w-direction 2. Length between grid points in w-direction [m]
	std_scaling	Ratio between standard deviation for specified component related to turbulence intensity input specified in main wind command block. If the std_scaling command is omitted, the SF is determined based on the u-variance, the SF for v and w direction are kept equal to u-direction (recommended) 1. Ratio to u-direction 2. Ratio to v-direction 3. Ratio to w-direction
	scaling_method	If the std_scaling command is used, this command specifies which method is used to scale the turbulent velocity components. If one of the dont_scale or factor_scaling command is used, this command is ignored. 1. (1=scaling is based on a standard deviation of the Mann box by convecting a point along the x coordinate at the velocity u_mean at the y-z center of the box – default, 2=scaling is based on a standard deviation calculated using the entire Mann box)
	dont_scale	If this command is used the normal scaling to ensure the specified turbulence intensity is bypassed. 1. (0=scaling according to specified inputs – default, 1=raw turbulence field used without any scaling)
	factor_scaling	If this command is used constant, scaling factors are applied. 1. Scaling factor in u-direction, F_u 2. Scaling factor in v-direction, F_v 3. Scaling factor in w-direction, F_w
	box_front	1. ('last_plane'=Advects turbulence data from end of file to beginning of file - compliant with the Mann turbulence model and generator, 'first_plane'=Advects turbulence from beginning of file to end of file - opposite of the Mann turbulence model and generator) Accepts one argument, 'first_plane' or 'last_plane' (default as of 13.1). Specifies whether the turbulence box front is the first or the last turbulence plane in the turbulence file. Using the argument 'last_plane' complies with the definition of the advection direction in the Mann turbulence model and built-in turbulence generator. The default was corrected in HAWC2 version 13.1 from 'first_plane' to 'last_plane'. This command was introduced in HAWC2 13.1.

11.3 Sub command block - flex

Block that must be included if the flex turbulence format is chosen.

Obl.	Command name	Explanation
*	filename_u	1. Filename incl. relative path to file containing flex turbulence u-component (example ./turb/flex-u.int)
*	filename_v	1. Filename incl. relative path to file containing flex turbulence v-component (example ./turb/flex-v.int)
*	filename_w	1. Filename incl. relative path to file containing flex turbulence w-component (example ./turb/flex-w.int)
	std_scaling	Ratio between standard deviation for specified component related to turbulence intensity input specified in main wind command block. 1. Ratio to u-direction (default=1.0) 2. Ratio to v-direction (default=0.8) 3. Ratio to w-direction (default=0.5)

11.4 File description of a user defined shear

In this file a user defined shear used instead, or in combination with one of the default shear types (logarithmic, exponential...). When the user defined shear is used the name and location of the datafile must be specified with the *wind – user_defined_shear* command. This command specifies the location of the file and activates the user defined shear. If this shear is replacing the original default shear the command *wind – shear_format* must be set to zero!

Only one shear can be present in a single file. The shear describes the mean wind profile of the u, v and w component of a vertical cross section at the rotor. The wind speeds are normalized with the mean wind speed defined with the command *wind – wsp*.

Line number	Description
1	Headline (not used by HAWC2)
2	Information of shear v-component. #1 is the number of columns, NC #2 is the number of rows, NR
3	Headline (not used by HAWC2)
4..+NR	Wind speed in v-direction, normalized with u-mean. # NC columns
1	Headline (not used by HAWC2)
+1..+NR	Wind speed in u-direction, normalized with u-mean. # NC columns.
1	Headline (not used by HAWC2)
+1..+NR	Wind speed in w-direction, normalized with u-mean. # NC columns
1	Headline (not used by HAWC2)
+1..+NC	Horizontal position of grid points (meteorological coo)
1	Headline (not used by HAWC2)
+1..+NR	Vertical position of grid points (meteorological coo)

11.5 Example of user defined shear file

```
# User defined shear file
3 4  # nr_v, nr_w     array sizes
# shear_v component, normalized with U_mean
0.0 0.0 0.0
0.0 0.0 0.0
0.0 0.0 0.0
0.0 0.0 0.0
# shear_u component, normalized with U_mean
1.0 1.0 1.0
1.0 1.0 1.0
1.0 1.0 1.0
1.0 1.0 1.0
# shear_w component, normalized with U_mean
0.0 0.0 0.0
0.0 0.0 0.0
0.0 0.0 0.0
0.0 0.0 0.0
# v coordinates
-50.0
0.0
50.0
# w coordinates (zero is at ground level)
0.0
60.0
100.0
200.0
```

11.6 File description of a user defined shear turbulence

The same file format is used as for *user_defined_shear* (see above). Instead of a normalized mean wind speed component, an additional turbulence scale factor is given by the user. The defined scale factors are applied on top of (multiplied with) the normal turbulence scaling coming from the turbulence model/box.

user_defined_shear_turbulence is an ad hoc and inconsistent scaling of a consistent turbulence field to obtain a non-homogeneous turbulence field, with the turbulence intensity varying with height. The HAWC2 developers do not recommend the use of this functionality, and users should be aware that by using the *user_defined_shear_turbulence* the correlation properties between the various components in space of the generated turbulence box will no longer be valid as originally intended (for example when using the Mann turbulence model). This feature will allow users to easily alter turbulence boxes with the 'cost' it no longer holds a reasonable physical representation of a turbulent wind field.

11.7 Example of user defined shear turbulence file

```
# User defined shear turbulence file
3 4  # nr_v, nr_w     array sizes
# std_v component (to be multiplied with turbulence scaling)
0.0 0.0 0.0
0.0 0.0 0.0
0.0 0.0 0.0
0.0 0.0 0.0
# std_u component (to be multiplied with turbulence scaling)
1.0 1.0 1.0
1.0 1.0 1.0
1.0 1.0 1.0
1.0 1.0 1.0
# std_w component (to be multiplied with turbulence scaling)
```

```
0.0 0.0 0.0
0.0 0.0 0.0
0.0 0.0 0.0
0.0 0.0 0.0
# v coordinates
-50.0
0.0
50.0
# w coordinates (zero is at ground level)
0.0
60.0
100.0
200.0
```

11.8 Sub command block - met_mast_wind

The *met_mast_wind* block can be used to specify time- and height-dependent wind speeds (u, uv, or uvw) from a data file.

The met-mast wind speeds are added to the usual wind speed; see Section 11.18. However, it is recommended to set the mean wind speed via the *wind.wsp* command and only specify fluctuations in the data file, as the turbulence box is only advected by the wind speed defined in *wind.wsp*.

Interpolation will be applied in time and also in height if *nlevels*>1. Note that below first *level* and above last *level*, the nearest met mast observation is used, i.e. no extrapolation is applied.

Obl.	Command name	Explanation
*	filename	1. Filename incl. relative path to file containing met mast data (example ./metmastdata.txt)
*	components	1. Number of wind speed components: 1=u, 2=u,v, 3=u,v,w
*	nlevels	1. Number of heights of observation of the masts met
*	levels	This command must be repeated *nlevels* times. 1. Level number. 2. Global z-coordinate of observation [m], i.e. negative numbers above ground
*	deltat	1. Time step [s] between rows in data file
	t0	1. Time of first row in data file First row in data file will be used from t=0 to t=t0. The default value is 0. For t>t0, time interpolation between the rows in the data file will be applied.

The format of the met_mast_wind data file is shown below. Each data row must contain *components* x *nlevels* values.

```
# Custom number of header lines
# starting with "#"
u1 v1 w1 ... u_nlevels v_nlevels w_nlevels  # t=0 to t=t0
u1 v1 w1 ... u_nlevels v_nlevels w_nlevels  # t=t0+deltat
u1 v1 w1 ... u_nlevels v_nlevels w_nlevels  # t=t0+2*deltat to t=time_stop
```

11.9 Sub command block - wakes

Block that must be included if the Dynamic Wake Meandering model is used to model the wind flow from one or more upstream turbines. The model is described, calibrated and validated in [1, 2], where [2] contains both a recalibration and a validation against measurements. In order to make the model function, two Mann turbulence boxes must be used. One for the meandering turbulence – which is a box containing atmospheric turbulence, but generated with a course resolution in the v,w plane (grid size of 1 rotor diameter). It is important that the turbulence vectors at the individual grid points represent a mean value covering a grid cube. It is also important that the total size of the box is large enough to cover the different wake sources including their meandering path. The resolution in the u-direction should be as fine a possible. The used length scale should correspond to normal turbulence condition. The other turbulence box that is needed is a box representing the micro scale turbulence from the wake of the upstream turbine itself. The resolution of this box should be fine (e.g. 128x128 points) in the v,w plane which should only cover 1 rotor diameter. The resolution in the u direction should also be fine, but a short length of the box (e.g. 2.5Diameter) is OK, since the turbulence box is reused. The length scale for this turbulence is significantly shorter than for the other boxes since it represents turbulence from tip and root vortices mainly. A length scale of 1/16 rotor diameter seems appropriate.

The two turbulence boxed are included by the following sub commands

```
begin mann_meanderturb;
    (parameters are identical to the normal Mann turbulence box, see above)
end mann_meanderturb;

begin mann_microturb;
    (parameters are identical to the normal Mann turbulence box, see above)
end mann_microturb;
```

The rest of the wake commands are given in the following table.

Obl.	Command name	Explanation
*	nsource	1. Number of wake sources. If 0 is used the wake module is by-passed (no source positions can be given in this case).
*	source_pos	Command that must be repeated nsource times. This gives the position of the wake source (hub position) in global coordinates. Wake source position given for down stream turbines are however not used in the simulations since they don't affect the target turbine. 1. x-pos [m] 2. y-pos [m] 3. z-pos [m]
*	op_data	Operational conditions for the wake sources. This command can be repeated nsource times to independently set the operation data of individual sources. If op_data appears once, the same operation data is used for all sources. 1. Rotational speed [rad/s] 2. Collective pitch angle [deg]. Defined positive according to the blade root coo, with z-axis from root towards tip. Note, this is opposite to the traditional notation for a pitch angle.
	ble_parameters	Parameters used for the BLE model used for developing the wake deficit due to turbulent mixing. 1. k_1 [-], default=0.10 2. k_2 [-], default=0.008 3. clean-up parameter (0=intermediate files are kept, 1=intermediate files are deleted), default=1
	microturb_factors	Parameters used for scaling the added wake turbulence according to the deficit depth and depth derivative. 1. k_{m1} [-], factor on deficit depth, default=0.60

Obl.	Command name	Explanation
		2. k_{m2} [-], factor on depth derivative, default=0.35
	multiple_deficit_method	Command that is used for choosing the best approach for handling multiple deficit 1. method (1=MAX operator (default), 2=Direct summation) In general it is recommended to use the MAX operator when the ambient free wind speed is below rated and the direct summation approach above rated wind speed.
	tint_meander	Turbulence intensity of the meander turbulence box. If this command is not used then the default turbulence intensity from the general wind commands is used (normal use) 1. Turbulence intensity [-]
	use_specific_deficit_file	File with the deficits used in the correct downstream distance is used instead of the build in deficit generator. The wind speed deficits are non-dim with the mean wind speed. 1. Filename incl. path (e.g. ./data/deficit.data)
	write_ct_cq_file	File including the local axial and tangential forces (non-dim) as function of blade radius is written. 1. Filename incl. path (e.g. ./res/ct_cq.data)
	write_final_deficits	File with the deficits used in the correct downstream distance is written. The windspeed deficits are non-dim with the mean wind speed. 1. Filename incl. path (e.g. ./res/ct_cq.data)

11.10 File description of a user defined wake deficit file

When another flow solve has been used to find the non-dim turbulence deficit, eg. using an actuator disc approach, this can replace the deficit otherwise calculated internally. This method cannot be used together with multiple deficits as only one deficit can be read.

Line number	Description
1	#1 Any single character (eg. #) #2 The number of rows (NR) #3 (optional) The rotor diameter. If not included, the diameter of the reference turbine is used.
2..+NR	Deficit non-dim with ambient free mean wind speed. #1 Radius (non-dim with rotor radius) #2 Deficit (non-dim with free mean wind speed). In the free

11.11 Example of user defined wake deficit file

```
# 121 178.0
0.000000000E+00  8.276891200E-01
2.500000000E-02  8.486243600E-01
5.000000000E-02  8.809613720E-01
7.500000000E-02  9.007844070E-01
1.000000000E-01  8.957724550E-01
1.250000000E-01  8.660702830E-01
1.500000000E-01  8.303410890E-01
1.750000000E-01  8.044380440E-01
2.000000000E-01  7.895593800E-01
2.250000000E-01  7.786515560E-01
2.500000000E-01  7.691674220E-01
2.750000000E-01  7.618372330E-01
```

```
3.000000000E-01  7.572012850E-01
3.250000000E-01  7.550918200E-01
3.500000000E-01  7.542137030E-01
3.750000000E-01  7.518827010E-01
4.000000000E-01  7.456746090E-01
4.250000000E-01  7.357259740E-01
4.500000000E-01  7.250309980E-01
4.750000000E-01  7.168460970E-01
5.000000000E-01  7.119492260E-01
5.250000000E-01  7.088296670E-01
5.500000000E-01  7.057605130E-01
5.750000000E-01  7.021459650E-01
6.000000000E-01  6.983228280E-01
6.250000000E-01  6.947171830E-01
6.500000000E-01  6.913423360E-01
6.750000000E-01  6.879199230E-01
7.000000000E-01  6.842943230E-01
7.250000000E-01  6.806519720E-01
7.500000000E-01  6.773263690E-01
7.750000000E-01  6.744196220E-01
8.000000000E-01  6.716445590E-01
8.250000000E-01  6.684818930E-01
8.500000000E-01  6.644046880E-01
8.750000000E-01  6.592242170E-01
9.000000000E-01  6.529686490E-01
9.250000000E-01  6.445576730E-01
9.500000000E-01  6.324201240E-01
9.750000000E-01  6.173566910E-01
1.000000000E+00  5.982423590E-01
1.028634580E+00  5.679249380E-01
1.058116050E+00  5.982195030E-01
1.088469450E+00  7.292761710E-01
1.119720570E+00  9.095984580E-01
1.151895960E+00  1.014958390E+00
1.185022960E+00  1.022114240E+00
1.219129700E+00  1.017341600E+00
...
8.903031630E+00  1.000285950E+00
9.165402860E+00  1.000213540E+00
9.435533870E+00  1.000143160E+00
9.713654150E+00  1.000066170E+00
1.000000000E+01  1.000018010E+00
```

11.12 Sub command block – tower_shadow_potential

This method models the tower shadow for an upstream turbine. However, for upstream turbines we recommend instead to always use the tower_shadow_potential_2 model that accounts for movement of the tower, which is especially necessary for floating turbines. The following block must be included if the potential flow tower shadow model is chosen.

Obl.	Command name	Explanation
*	tower_offset	The tower shadow has its source at the global coordinate z axis. The offset is the base point for section 1 1. Offset value (default=0.0)
*	nsec	Command that needs to present before the radius commands. 1. Number of datasets specified by the radius command.
*	radius	Command that needs to be listed nsec times. 1. z coordinate [m] 2. Tower radius at z coordinate [m]

11.13 Sub command block – tower_shadow_jet

This method models the tower shadow for an downstream turbine. However for downstream turbines we recommend instead to always use the tower_shadow_jet_2 model that accounts for movement of the tower, which is especially necessary for floating turbines. The following block must be included if the model based on the boundary layer equations for a jet is chosen.

Obl.	Command name	Explanation
*	tower_offset	The tower shadow has its source at the global coordinate z axis. The offset is the base point for section 1 1. Offset value (default=0.0)
*	nsec	Command that needs to present before the radius commands. 1. Number of datasets specified be the radius command.
*	radius	Command that needs to be listed nsec times. 1. z coordinate [m] 2. Tower radius at z coordinate [m] 3. Cd drag coefficient of tower section (normally 1.0 for circular section, but this depends heavily on the reynold number)

11.14 Sub command block – tower_shadow_potential_2

This method models the tower shadow for an upstream turbine. This potential model is principally similar to the potential flow model described previously but differs in the way that the shadow source is moved and rotated in space as the tower coordinate system is moving and rotating. It is also possible to define several tower sources e.g. if the tower is a kind of tripod or quattropod. Just include more tower_shadow_potential_2 blocks if more sources are required.

The coordinate system that the shadow method is linked to is specified by the user, e.g. the mbdy coordinate from the tower main body. To make sure that the tower source model is always linked in the same way as the tower (could be tricky since the tower is fully free to be specified along the x,y or z axis or a combination) the base coordinate system for the shadow model is identical to the coordinates system obtained by the local element coordinates, where the z axis is always pointing from node 1 towards node 2. This is the reason that the tower radius input has to specified with positive z-values, see below. The following block must be included if the tower shadow method 3 is chosen.

Obl.	Command name	Explanation
*	tower_mbdy_link	Name of the main body to which the shadow source is linked. 1. mbdy name
*	nsec	Command that needs to present before the radius commands. 1. Number of datasets specified by the radius command.
*	radius	Command that needs to be listed nsec times. 1. z coordinate [m] (allways positive!) 2. Tower radius at z coordinate [m]

11.15 Sub command block – tower_shadow_jet_2

This method models the tower shadow for an downstream turbine. This jet model is principally similar to the jet model described previously but differs in the way that the shadow source is moved and rotated in space as the tower coordinate system is moving and rotating. It is also possible to define several tower sources e.g. if the tower is a kind of tripod or quattropod. Just include more tower_shadow_jet_2 blocks if more sources are required.

The coordinate system that the shadow method is linked to is specified by the user, e.g. the mbdy coordinate from the tower main body. To make sure that the tower source model is always linked in the same way as the tower (could be tricky since the tower is fully free to be specified along the x,y or z axis or a combination) the base coordinate system for the shadow model is identical to the coordinates system obtained by the local element coordinates, where the z axis is always pointing from node 1 towards node 2. This is the reason that the tower radius input has to specified with positive z-values, see below. The following block must be included if the tower shadow method 4 is chosen.

Obl.	Command name	Explanation
*	tower_mbdy_link	Name of the main body to which the shadow source is linked. 1. mbdy name
*	nsec	Command that needs to present before the radius commands. 1. Number of datasets specified by the radius command.
*	radius	Command that needs to be listed nsec times. 1. z coordinate [m] 2. Tower radius at z coordinate [m] 3. C_d drag coefficient of tower section (normally 1.0 for circular section, but this depends heavily on the reynold number)

11.16 Sub command block – user_wind_dll

A user defined DLL can be used to provide additional wind velocity on top of what is already defined by wind input in HAWC2. During simulation, HAWC2 calls the DLL with position as argument, and the DLL must provide the wind velocity in that position on return. Apart from the position, HAWC2 also parses time and user-specified arguments to the DLL - the user-specified arguments are defined in the same output block format as is used for type2_dlls and hawc_dlls and as regular output. See Section B for further details.

Obl.	Command name	Explanation
*	filename	Path and name of DLL.
	dll	deprecated alternative to filename.
*	subroutine	Subroutine name to call in DLL.
	refsys	Reference coordinates for position (in) and velocity (in/out). 0. meteorological coordinates (default) 1. global coordinates
	begin output; <output block> end output;	Output block definition which can be used to provide additional user-specified input to the DLL, see example in Section B . Note that the only output types that can be used are: - `general`, - `dll`, - `constraint`, and - `mbdy`.

11.17 Sub command block – turb_export

With this sub command block, a mann format turbulence box including information from shear, wakes, tower shadow etc. is written. Same data point positions are used as specified in the turbulence module including the parameters specified for the originally used mann turbulence box.

Obl.	Command name	Explanation
*	filename_u	Filename of turbulence box with axial turbulence 1. File name
*	filename_v	Filename of turbulence box with lateral turbulence 1. File name
*	filename_w	Filename of turbulence box with vertical turbulence 1. File name
	samplefrq	1. Sample frequency
	time_start	1. Time at which the the turbulence recording will start
	nsteps	1. Number of steps between output
	box_dim_v	1. Number of points in v-direction 2. Distance between points in v-direction
	box_dim_w	1. Number of points in w-direction 2. Distance between points in w-direction

11.18 How the wind speed is constructed

The wind speed is finally constructed based on the following user inputs (and in the meteorological coordinate system:

```
wsp = action_windspeed_u + gust
   + (wsp_mean*wind_ramp_factor+wind_ramp_abs)*shear_factor
   + (wsp_mean*wind_ramp_factor+wind_ramp_abs)*user_defined_shear
   + met_mast_wind + dwm_deficit_u*wind_ramp_factor
   + dwm_turb*wind_ramp_factor
   + turb * scaling * user_defined_shear_turbulence * wind_ramp_factor
   + user_wind_dll velocity
```

The above commands are explained in more detail in the sections above. Some additional clarifications are as follows:

- `action_windspeed_u` corresponds to the DLL action command `wind windspeed_u`.
- `wsp_mean` is the mean wind speed as set by the `wsp` command.
- `shear_factor` is the determined by the shear type as set by the `shear_format` command.
- `scaling` is affected by the commands `std_scaling`, `dont_scale`, and/or `factor_scaling`. See also the description in the Mann section above.
- `dwm_deficit_u` is the velocity deficit in the wake as given by the Dynamic Wake Meandering model (DWM).
- `dwm_turb` is the added turbulence due to the wake as given by the DWM model.

After transforming to the global coordinate system, the tower shadow deficit is added as follows:

```
wspG = wspG*tower_shadow_factor
```

12 Aerodynamics

In HAWC2 there are different fidelity aerodynamic models available for both HAWTs and VAWTs. In addition, there are different sub-models to model different effects, such as the dynamic inflow model and unsteady 2-D airfoil aerodynamic model (usually referred to as the dynamic stall model). The different models for the simulation are chosen by command blocks including different commands. Some recommendations are listed as follows to ease the choice of the models.

1) For both HAWTs and VAWTs, the MHH Beddoes dynamic stall model is always recommended to be turned on, even for steady-state simulations. This is because the model includes lift, drag and moment terms that depend on the rate of rotation and acceleration of the airfoil section. These terms will generally be constant and non-zero for steady state simulations even with stiff turbines and uniform inflow. For more details, please see [3, 4].

2) For aeroelastic simulations of HAWTs, the aerodynamic model have different fidelities and different computational efforts. The BEM model with dynamic inflow implemented on a polar grid, as described in [5], is enabled with the command 'induction_method 1' in the aero command block.

There are higher fidelity models available since HAWC2 13.0: the near wake model and vortex cylinder model that compute the effects of swept blades and non-planar rotor geometry on the aerodynamic induction and consequently on the aerodynamic loads. For details see [6, 7, 8]. The following commands in the 'aero' block will enable both the near wake model and the vortex cylinder model, which corresponds to the highest fidelity modeling available in HAWC2. The computational time will be increased compared to BEM modeling, but the results for curved and deflected blades will be closer to lifting line or CFD simulations as shown in the references cited above.

```
induction_method   2 ;
begin bemwake_method ;
  vortex_cylinder_model 1;
  wake_rot_effect 1;
end bemwake_method ;
begin nearwake_method ;
   nw_sweep 1;
end nearwake_method ;
```

12.1 Main command block - aero

This module set up parameters for the aerodynamic specification of the rotor. It is also possible to submit aerodynamic forces to other structures as example the tower or nacelle, but see chapter (Aerodrag) regarding this. The module can be added as many times as requested if multiple aerodynamic rotors are needed.

Obl.	Command name	Explanation
(*)	name	Name of rotor (in case of multiple rotors defined this is obligatory.)
*	nblades	Must be the first line in aero commands! 1. Number of blades

Obl.	Command name	Explanation
*	hub_vec	Link to main-body vector that points downwind from the rotor under normal conditions. This corresponds to the direction from the pressure side of the rotor towards the suction side where the coordinate system is normally taken from the main shaft system. (For VAWTs: Link to main-body vector that defines the rotational direction. Currently it is only possible to model VAWTs that are clockwise rotating, if seen from above) 1. mbdy name or 'old_input' if old_htc_structure format is applied. 2. mbdy coo. component (1=x, 2=y, 3=z). If negative the opposite direction used. Not used together with old_htc_structure input (specify a dummy number). 3. Node number (optional). Node number on mbdy where rotor center is located. 'last' can also be used (default if no value is present).
*	link	Linker between structural blades and aerodynamic blades. There must be same number of link commands as nblades! 1. blade number 2. link chooser – options are - mbdy_c2_def (used with new structure format) - blade_c2_def (used with old structure format, see description below in this chapter) 3. mbdy name (with new structure format), not used to anything with old structure format.
*	ae_filename	1. Filename incl. relative path to file containing aerodynamic layout data (example ./data/hawc2_ae.dat)
*	pc_filename	1. Filename incl. relative path to file containing profile coefficients (example ./data/hawc2_pc.dat)
*	induction_method	1. Choice between which induction method that shall be used (0=none, 1=normal BEM dynamic induction, 2= Near Wake induction method, 3= VAWT Actuator Cylinder model, 4= VAWT Actuator Cylinder model coupled with Near Wake induction model providing tip loss correction for H-VAWTs)
	hub_type	1. Defines the type of hub, to distinguish between HAWT and VAWT. (1=HAWT, 2=VAWT) (default=1). Note: This will be automatically set to 1 if induction_method=1 or 2; it will be automatically set to 2 if induction_method=3 or 4. So, this command only needs to be included if using induction_method=0.
	only_update_r_mono_incr	1. Should the induction model be updated if the blade radius doesn't monotonically increase towards the tip? Then some assumptions in the aerodynamic induction models are no longer valid and the crashes may occur. (0=always update, 1=only update if the radius is increasing monotonically, otherwise keep values from last time step)(default=0)
	rotate_sec	Define rotation of section relative to default orientation. This command is needed when simulating a counter-clockwise rotating rotor. 1. θ_x (must be 0.0) 2. θ_y (0.0 (default, for clockwise-rotating rotor), 180.0 (for counter-clockwise rotating rotor)) 3. θ_z (must be 0.0)

Obl.	Command name	Explanation
		An illustrated example to convert from CW to CCW is available in the HAWC2Public/examples repository.
*	aerocalc_method	1. Choice between which aerodynamic load calculation method that shall be used. (0=none, 1=normal)
*[1]	aerosections	Number of aerodynamic calculation points at a blade. The distribution is controlled via the "aero_distribution" command, see below. Note, this command is not allowed in combination with "aero_distribution=ae_file". 1. Number of points at each blade.
	aero_distribution	1. Distribution method of aerodynamic calculation points. Options are: - “cosine” (default). The distribution is performed automatically using a cosine distribution which gives closest spacing at root and tip. - "default". Same as "cosine". Deprecated. - “linear”. The distribution is performed automatically using uniform spacing along the curved blade length. - “ae_file” set. The distribution is given with same spacing as values in the ae_file with set number corresponding to the specified blade number. 2. blade number (only used for "ae_file")
*	ae_sets	Set number from ae_filename that is linked to blade 1,2,...,nblades 1. set for blade number 1 2. set for blade number 2 . . . nblades. set for blade number nblades
*	tiploss_method	1. Choice between which tip-loss model that shall be used (0=none, 1=prandtl (default), 2=Method described in [9]. Method 2 is only intended to be used when coupled to actuator disc methods, where a total velocity is sampled at the rotor disk and the induced velocity is generally not known. Method 2 modifies the angle of attack α, such that the lift is reduced to the size proposed by Shen[10]. In addition to the force reduction proposed by Shen, the change in angle of attack also causes a force rotation. This approach is more consistent and gives better results for torque and power. In contrast to the recommended method 1(Prandtl), this method can be used if the induction calculation is turned off) 2. Optional tuning parameter for method 2. (The parameter is called c2 and defaults to 21. See equation in Shen[10] between eq. 25 and eq 26).

[1] Obligatory except if aero_distributions="ae_file"

Obl.	Command name	Explanation
*	dynstall_method	1. Choice between which unsteady airfoil aerodynamics model that shall be used (0=none, 1=Stig Øye method (only stalled flow part, not recommended), 2 or 3=unified method combining MHH Beddoes method for sections without flaps and Gaunaa-Andersen-Bergami method with deformable Trailing Edge Flaps. For backwards compatibility, the default values for the attached flow indicial function terms are identical to the values used in the HAWC2 releases before 12.9. They correspond to the default values of the previous MHH model when choosing dynstall_method 2 and those for the previous ATEFlap model when choosing dynstall_method 3, see also Section 12.3).
	3d_correct_method	Airfoil Cl values from the pc_file is modified for 3D effects. 1. Correction method (1=Snel method for correction of Cl values)
	external_bladedata_dll	Blade structural data are found in an external encrypted dll. If this command is present the following command lines shall not be present (ae_filename, pc_filename and ae_sets). 1. Company name (that has been granted a password, eg. dtu). 2. Password for opening this specific dll, eg. test1234 3. path and filename for the dll. eg. ./data/encr_blade_data.dll
	output_profile_coef_filename	Interpolated profile coefficients at all aerodynamic calculation points are written into a data file. This command can not be used in combination with encrypted_profile_coef_filename. 1. path and filename for the dll. eg. ./res/aero_profiles.dat

12.2 Sub command block – dynstall_so

Block that may be included if the Stig Øye dynamic stall method is chosen. If not included defaults parameters are automatically used. The Stig Øye model lacks the attached flow unsteady aerodynamics model and may lead to unphysical aeroelastic vibrations for example due to missing torsion rate terms.

Obl.	Command name	Explanation
	dclda	1. Linear slope coefficient for unseparated flow (default=6.28)
	dcldas	1. Linear slope coefficient for fully separated flow (default=3.14)
	alfs	1. Angle of attack [deg] where profile flow is fully separated. (default=40)
	alrund	1. Factor used to generate synthetic separated flow Cl values (default=40)
	taufak	1. Time constant factor in first order filter for F function (default=10.0). Internally used as tau=taufak*chord*vrel

12.3 Sub command block – dynstall_mhh or dynstall_ateflap

This Block may be included if the unified unsteady airfoil aerodynamics model is chosen that combines the MHH model [11, 4, 12] and the ATEFlap model described in [13].

These models were different until HAWC2 12.9 and are combined since HAWC2 13.0. For backwards compatibility, both names of the command block are recognized. If the block is not part of the .htc file, default values are used. The default values for the indicial function used in attached flow depend on which dynstall_method is chosen, again to ensure backwards compatibility. If dynstall_method 2 is chosen, a two term indicial function is used with the same default values as in the dynstall_MHH model up to HAWC2 12.9, approximating the response of a flat plate. If dynstall_method 3 is chosen, a three term indicial function method is used with the same default values as the dynstall_ATEFlap model up to HAWC2 12.9, approximating the response of a NACA 64-418 profile. See the following table for the exact values. Aside from these indicial function default values, dynstall_method 2 and 3 are identical since HAWC2 13.0.

The unified dynamic stall model is the recommended model for a turbine with or without trailing edge flaps. It consists of an attached flow part that covers the Theodorsen effect as well as torsion rate terms and added mass terms, as well as a dynamic stall part that simulates trailing edge stall. The Theodorsen effect, that is modeled as an effective angle of attack lagging behind the quasi steady angle of attack, is deactivated based on the separation point position, [4]. Typically, this makes it unnecessary to deactivate the model in more demanding cases such as standstill. However, for very fast, large amplitude changes of angle of attack, combined with low relative velocities, which may for example occur for a VAWT at very low tip speed ratio, angles of attack around 180 degrees may be reached faster coming from the attached flow region than the flow can separate. This can lead to unphysical discontinuities in lift and drag coefficient and the user is advised to either tune the time constants or deactivate the model in this case.

If a flap section is defined, the model requires a .ds input file containing pre-processed steady aerodynamic data for the blade sections containing a flap (see Section 12.12 for the file specifications). Sections without any flap are attributed steady input data according to the aerodynamic layout specified in the ae_filename.

The dynamic stall part of the model interpolates between an attached flow lift coefficient curve, which extends the linear lift region of the airfoil polar, and a fully separated lift coefficient. The interpolation is done according to a separation point position that is between 0 (separation point at leading edge: fully separated flow) and 1 (separation point at trailing edge: fully attached flow). How these lift coefficients and the steady state separation point position are determined is described in [11]. Since HAWC2 13.0, the model will deactivate itself for the aerodynamic sections where 1) the thickness is above a user defined maximum value (default: 99.99% thickness), 2) a reasonable attached flow region couldn't be found or 3) the determined steady state separation point is outside of the airfoil chord for some angle of attack values. This deactivation will likely only trigger for sections close to the root, that are either a cylinder or interpolated between a very thick airfoil and a cylinder. A logfile message will inform about the deactivation. If the airfoil thickness limit is exceeded, the airfoil data preprocessor will not run so output values of for example attached flow lift gradient in the deactivation logfile message will be dummy values. The maximum allowable thickness max_thickness, the minimum allowable linear region lift gradient min_dclda and the maximum allowable separation point value max_fsep where the model is still active can be user defined, see the following table.

The user can choose to output the dynamic stall data for all airfoil section to ensure that the automatic preprocessing works as intended. The output files contain the following information: The first 7 lines contain a logical determining if the model was deactivated (T/F), the zero lift AOA alfa0, the linear lift region lift gradient dclda, the lower AOA of full separation alfa_fs_l, the AOAs at the border of the attached flow region alfa_sl_neg and alfa_sl_pos and the higher AOA of full separation alfa_fs_u. Then follow 6 columns of preprocessed airfoil data: the range of AOAs in the first column, and then as function of those AOAs the limited attached flow lift coefficient cl_att_lim, the lift coefficient cl_input given in the input polar data, the linear lift coefficient cllin, the fully separated lift coefficient cl_fullsep and the separation point position f_point.

Due to the torsion rate and added mass terms, the lift coefficients predicted by this unsteady airfoil aerodynamics model can reach very high values. The torsion rate lift coefficient is $c_{l,tors} = \pi T_0 \dot{\theta}$ (Eq (5) in [4]), and the added mass normal force coefficient $c_{n,acc} = -\pi T_0 \frac{\ddot{y}}{U}$ (Eq (13) in [4]). The term T_0 in these equations is $T_0 = c/(2U)$ with the chord c and the relative velocity U; $\dot{\theta}$ is the rate of rotation of the airfoil and $\ddot{y}$ is the acceleration of the airfoil perpendicular to the chord. The lift coefficient from Eq (5) has a relative velocity in the denominator. The normal force coefficient from Eq (13), which will have components in lift and drag coefficient depending on the angle of attack, has a relative velocity squared in the denominator. Both coefficients can reach very large values if the relative velocity is close to zero. However because they are multiplied by the relative velocity squared to compute the lift and drag forces, these large values will not result in large forces. Thus if the code predicts very large lift and drag coefficients, the relative velocity and, most importantly, the forces should be investigated. If the forces are reasonable, then it is safe to assume that the large coefficients are not problematic but instead correctly modeling the aerodynamic forces due to torsion rate or added mass.

Obl.	Command name	Explanation
	a1	1. Coefficients of the exponential potential flow step response approximation: Phi(s)=1-A1*exp(-b1*s)-A2*exp(-b2*s). (default when dynstall_method 2= 0.165)
	a2	1. Coefficients of the exponential potential flow step response approximation: Phi(s)=1-A1*exp(-b1*s)-A2*exp(-b2*s). (default when dynstall_method 2= 0.335)
	b1	1. Coefficients of the exponential potential flow step response approximation: Phi(s)=1-A1*exp(-b1*s)-A2*exp(-b2*s). (default when dynstall_method 2= 0.0455)
	b2	1. Coefficients of the exponential potential flow step response approximation: Phi(s)=1-A1*exp(-b1*s)-A2*exp(-b2*s). (default when dynstall_method 2 =0.300)
	update	Choice between update methods: 1. 1 (default)=>update aerodynamics all iterations all timesteps; 0=>only update aerodynamics first iteration each new timestep
	taupre	1. Non-dimensional time-lag parameters modeling pressure time-lag. Default value =1.5
	taubly	1. Non-dimensional time-lag parameters modeling boundary layer time-lag. Default value=6.0
	only_potential_model	1. 0(default)=>run full unsteay airfoil aerodynamics model; 1=>run only attached flow part
	disable_att_flow_mem_effect	1. 0(default)=>enable attached flow memory effects; 1=>disable attached flow memory effects so that only non-circulatory terms in attached flow are computed
	max_cl_attached	1. Maximum value of lift coefficient for attached flow.
	flap	Command to define a flap section. The flap is defined on all the blades of the rotor. Command syntax: 1. Starting point of flap section given as distance from the root along the half chord line [in m]. 2. Ending point of flap section given as distance from the root along the half chord line [in m]. Should be larger than the starting point value. 3. Filename incl. relative path to .ds file containing pre-processed aerodynamic steady input data. See .ds file specifications in the following paragraph. N.B. The locations along the blade refer to the curved length. They are given along the half-chord line (as the layout in ae_file). A maximum of 99 flap sections can be defined.
	ais	Coefficients for the indicial response exponential function (default values given for dynstall_method 3): 1. A1 (default= 0.1784) 2. A2 (default=0.07549) 3. A3 (default=0.3933)

Obl.	Command name	Explanation
		Default coefficients describe the step response of a NACA 64-418 profile, where t/c=0.18.
	bis	Coefficients of the exponential potential flow step response approximation (default values given for dynstall_method 3): 1. B1 (default= 0.8000) 2. B2 (default= 0.01815) 3. B3 (default= 0.1390) Default coefficients describe the step response of a NACA 64-418 profile, where t/c=0.18.
	hystar	1. Camberline coef. (default= -4.675844E-003)
	fylestar	1. Camberline coef. (default= +4.155446E-004)
	fdydxle	1. Camberline coef. (default= +7.236104E-003)
	gdydxle	1. Camberline coef. (default= +3.309147E-003)
	min_dclda	1. Minimum linear region lift gradient (The model will be deactivated for an aerodynamic section if the linear region lift gradient is smaller than this value. Default = 3.0)
	max_fsep	1. Maximum separation point value (The model will be deactivated for an aerodynamic section if the maximum separation point value is larger than this value. Default = 1.2)
	max_thickness	1. Maximum relative thickness value (The model will be deactivated for an aerodynamic section if the relative thickness is larger than this value. Default = 99.99%)
	output_polar_filename	1. Filename for detailed output of the processed airfoil data. One file per aerodynamic section will be saved, where the user defined filename will be extended by the blade number and position along the curvedlength.
	n_static_ds_iter	1. Number of dynamic stall model calls during each aerostructural iteration of the static solver (default=30)

The camber line coefficients describe the camber line deformation shape induced by the flap; they are computed according to the thin-airfoil model described in [14]. Hystar and fylestar are dimensionless parameters corresponding to the shape integrals Hy and FyLE normalized by the half-chord length. The default coefficients refer to a 10% chord length flap with a continuous deformation shape, describing a circular arc, whose chord forms an angle of 1 degree with the horizontal axis.

12.4 Sub command block – aero_noise

If this command block is used, aero-acoustic calculations are performed. The blade is discretized spanwise into elementary blade sections corresponding to the aerodynamic calculation points of the main command block – aero, i.e. as defined by the command 'aerosections'. Aerodynamic noise is calculated for each of these blade sections and subsequently added at the observer location(s) assuming incoherent noise sources. Only geometrical spreading is considered for the noise propagation between blade sections and observer. Details of the implementation for the turbulent inflow, trailing edge and stall noise models can be found in Bertagnolio et al, *A combined aeroelastic-aeroacoustic model for wind turbine noise: verification and analysis of field measurements*, Wind Energy (20), 2017. As for the loading-thickness noise model, the implementation is described in Bertagnolio et al, *A temporal wind turbine model for low-frequency noise*, InterNoise (Conf. Proc.), 2017.

Obl.	Command name	Explanation
	noise_mode	1. Noise mode (0=no noise calculation, 1=compute noise at each time-step on the fly, 2=store aerodynamic data for later noise calculation as post-processing (using option 3 or 4), 3=compute noise at each time-step using stored data, 4=compute steady-state noise using stored data and rotor disk azimuthal sector averaging yielding large time-saving) (default=0)
	noise_start_end_time	Start and end time for noise computation. 1. Start time, t_0 [s] 2. End time, t_1 [s] (default: at all time)
	noise_deltat	1. Time-step for noise calculation (default: at each HAWC2 time-step)
	noise_azimuth_sectors	1. Number of rotor disk azimuthal sectors when running noise_mode=4 (default=16)
	atmospheric_pressure	1. Atmospheric pressure [Pa] (default=101325.)
	temperature	1. Temperature [deg. Celsius] (default=20.)
	octave_bandwidth	1. Octave band frequency centers used for defining noise spectra. Options are: 1, 3, 12 and 24 (default=3)
	spl_min_max_frq	Minimum and maximum computed frequency for integrated sound pressure level calculations. 1. Minimum frequency, fr_{min} [Hz] 2. Maximum frequency, fr_{max} [Hz] (default: all octave band frequency centers are used)
	turbulent_inflow_noise	1. Turbulent inflow noise model (0=using Von Karman turbulence spectra, 1=using Mann atmospheric turbulence model) (default=0)
	turbulent_inflow- _thickness_correction	1. Turbulent inflow thickness correction (0=none, 1=correction is added to turbulent inflow noise) (default=0)
	mann_turbulence_parameters	Mann turbulence parameters. 1. L: turbulent integral length (default=29.7m) 2. $\alpha\varepsilon^{2/3}$: energy level (default=1.0) 3. γ: anisotropy factor (default=3.7) If any value is negative, then its default value is assumed.
	surface_roughness	1. Surface roughness, z0 (If specified, it is used to re-define the Mann turbulence parameters)
	trailing_edge_noise	1. Trailing edge model (0=none, 5=TNO 'frba' model, 31=Amiet 'frba' model, 41=Amiet 'asfi' model) (default=0)
*	bldata_filename	1. Filename incl. relative path defining tabulated input data for trailing edge noise model.
	trailing_edge_serration	Trailing edge serration model parameters. 1. R_1 Inboard radius [m] 2. R_2 Outboard radius [m] 3. L_{ser} Serration periodic span length [m] 3. H_{ser} Serration crest to trough height [m]
	stall_noise	1. Stall noise model (0=none, 1=Amiet based model, 2=Full formulation) (default=0)
	stall_separation	Stall separation definition. 1. Stall separation (1=tabulated and given in bldata_filename, 2=use dynamic stall model, 3=forced separation location) (default=1) 2. Forced separation location (x/C[-]: if positive on suction side, if negative on pressure side)

Obl.	Command name	Explanation
	tip_noise	1. Tip noise model (0=none, 1=not implemented yet!!!) (default=0)
	loading_noise	1. Loading-thickness noise model (0=none, 1=based on tabulated Cl, 2=based on Cp distribution from tabulated data, 3=based on Cl from HAWC2 aerodynamics) (default=0) This model does not work with noise_mode=4.
	loading_data_filename	1. Filename incl. relative path defining tabulated input data for loading-thickness noise.
*	xyz_observer	Position of observer in global reference system. 1. x [m] 2. y [m] 3. z [m] More than one observer is allowed (but must be <256).
	output_filename	1. Filename incl. relative path for output log file.

12.5 Sub command block – bemwake_method

Parameters used to calculate the steady state induction and dynamic induction. If not included defaults parameters are automatically used.

Obl.	Command name	Explanation
	nazi	1. Number of azimuthal points in the induction grid. A high number increased accuracy but slow down the simulation time. Default is 16.
	fw	Dynamic time constants and mixing ratio contribution for the far wake part of the induction. 1. Mixing ratio, default is 0.4153 2. k_3 (poly. coef. for r/R sensitivity) default=0.0 3. k_2 (poly. coef. for r/R sensitivity) default=-0.1667 4. k_1 (poly. coef. for r/R sensitivity) default=0.0881 5. k_0 (poly. coef. for r/R sensitivity) default=2.0214
	nw	Dynamic time constants and mixing ratio contribution for the near wake part of the induction. 1. Mixing ratio, default is 0.5847 2. k_3 (poly. coef. for r/R sensitivity) default=0.0 3. k_2 (poly. coef. for r/R sensitivity) default=-0.7048 4. k_1 (poly. coef. for r/R sensitivity) default=0.1819 5. k_0 (poly. coef. for r/R sensitivity) default=0.7329
	a-ct-filename	Filename for a user defined relation between a and ct.
	a_ct_table	Filename for a user defined table of axial induction factor a and the thrust coefficient C_T (Note: the value of C_T in the table should be monotonically increasing). This will overwrite the default polynomial relationship between a and C_T. This flag is not able to be used together with a-ct-filename. The data format for the file is described in Section. 12.18.
	custom_tiploss	Filename for a user defined tip/root loss factor. Filestructure: One number in the first line gives the number of radial stations specified in the file. Following lines have two numbers: non-dimensional radius $0 < r/R < 1$ followed by tip/root loss factor $0 < F_{custom} < 1$.

Obl.	Command name	Explanation
		It is applied on the $a = f(CT)$ relation as $a = f(C_T/(FF_{custom}))$ where F is the regular tip loss factor. This allows e.g. implementation of a user defined root loss model by specifying F_{custom} going from 0 at the root towards 1 at or before the tip. In that way F_{custom} and the regular tiploss factor F can be used together.
	radial_induc	1. Radial induction model (0=none , 1=Radial induction model described in Section 2.8 of [5])(default=0)
	only_lift_for_momentum-_balancing	(0=default, both lift and drag forces contribute to momentum balancing; 1=only lift force contributes to momentum balancing)
	wake_rot_effect	(0=default, exclude the pressure drop due to the wake rotation effect in the wake; 1=include the pressure drop due to the wake rotation effect in the wake. This is described in Section 3.2 and 3.3 of [15])
	tip_loss_sectional_angle	(0=default, use the flow angle seen in the rotor-polar coordinate system (inflow angle) to calculate the tip loss factor described in Section 2.3 of [5]; 1=use the flow angle seen by the section (angle of attack plus deformed twist angle) to calculate the tip-loss factor. This is described in Section 5.2 of [8]. The results of using two different methods will be different if the blade has noticeable out-of-plane geometry.)
	vortex_cylinder_model	(0=default, do not use vortex cylinder model; 1=use the vortex cylinder model as a correction to the BEM method. The method is able to model blade non-planar effects on the aerodynamic induction. The method is described in [8]. Since the radial induction is calculated from the vortex cylinder model, the flag of radial_induc will not be functioning.)
	n_static_bem_iter	1. Maximum number of induction model calls per aerostructural iteration of the static solver (default=100)
	static_bem_conv_criterion	1. Convergence criterion of induction model in static solver, compared to the squared mean induction factor difference between iterations (default=1E-8)

12.6 Sub command block – nearwake_method

The near wake model implementation in HAWC2 couples the lifting line theory based near wake model for trailed vorticity with the modified HAWC2 BEM as a far wake model. Inherently included in the trailed vorticity computations are the influences of the tip and root vortices; a 'root-loss' model is otherwise not included in HAWC2. The model is described in [16, 17] and has been shown to improve the dynamic blade loading in the presence of turbulence, blade vibrations and flap actuations.

In case of strong load gradients on the blade due to for example flaps at fixed angle or other aerodynamic devices activating the near wake model leads to an improved steady state load distribution. When used in this case with a prescribed point distribution along the blade (defined in the ae-file) then sudden changes in the point density (for example close to the flap) should be avoided as they can lead to numerical instability of the model. As with any vortex model, care should be taken when operating in deep stall conditions, such as extreme yaw conditions in standstill.

Since HAWC2 13.0 the near wake model is able to model the effects of blade sweep on the induced velocity at the blade [6, 7, 18]. The influence of non-straight bound vortex can and should also be included. However, for the purpose of backwards compatibility, the model extension for swept blades is not enabled by default.

Obl.	Command name	Explanation
	only_one_nw_function	Dynamic accuracy, see Section 6 in [17] for details. (0=2 exponential functions used; 1=default, 1 exponential function used: minimally lower accuracy but almost twice as fast)
	only_axial_nw	(0=default, near wake model used for both axial and tangential induction; 1= near wake model used for axial induction only)
	fast_nwm	(0=full iteration loop of the near wake model; 1= default, helix angle and vortex filament length fixed during iteration loop, almost identical results, much faster)
	fixed_kfw	kfw (0<kfw<1). This coupling factor will be used and is fixed during the computation. Not using this command means the coupling factor will be computed automatically and dynamically updated each time step (default, see Section 5 in [16] for details)
	r_core	r_core determines the vortex core radius (default=0: no vortex core is used). The implementation is in beta version and not validated.
	nw_sweep	(0=default, use the near-wake model that does not consider the effects of blade sweep on the aerodynamic induction. [16, 17]; 1=use the near-wake model that models the effects of blade sweep on the aerodynamic induction. The extension to the model is described in [6, 7])
	nw_curved_bound	This flag only works if nw_sweep=1. (1=default, includes the curved bound vortex effect. [7]; 0=does not include the curved bound vortex effect. Ignoring the curved bound vortex will lead to wrong results for swept blades, see [7, 18])

12.7 Sub command block – vawtwake_method

VAWT dynamic inflow parameters. The model implemented in the code is described in [19]. The model uses two parallel first order filters for the near- and far-wake induction, respectively. This is similar to the BEM dynamic inflow model. However for the VAWT model, the non-dimensional time constants, which can be given as user defined input as shown in the table below, are multiplied by the radius of the actuator cylinder divided by the free wind speed. Currently there is no dependency of the time constants on distance from the blade tip or on average induction factor implemented in the VAWT dynamic inflow model.

Obl.	Command name	Explanation
	nazi	1. Number of azimuthal points in the induction grid. A high number increased accuracy but slow down the simulation time. Default is 36.
	fw	Dynamic time constants and mixing ratio contribution for the far wake part of the induction. 1. Mixing ratio, default is 0.4 2. k_3 dummy value, currently not used in the model 3. k_2 dummy value, currently not used in the model 4. k_1 dummy value, currently not used in the model 5. k_0 fw time constant, default=2.0
	nw	Dynamic time constants and mixing ratio contribution for the near wake part of the induction. 1. Mixing ratio, default is 0.6 2. k_3 dummy value, currently not used in the model

Obl.	Command name	Explanation
		3. k_2 dummy value, currently not used in the model 4. k_1 dummy value, currently not used in the model 5. k_0 nw time constant, default=0.5
	induc_due_to_qt	(0=default, inductions only due to normal loading Qn; 1=inductions due to both normal loading Qn and also tangential loading Qt.)

12.8 Data format for the aerodynamic layout

The format of this file which in the old HAWC code was known as the hawc_ae file is changed slightly for the HAWC2 input format. The position of the aerodynamic center is no longer an input value, since the definition is that the center is located in $C_{1/4}$ with calculated velocities in $C_{3/4}$.

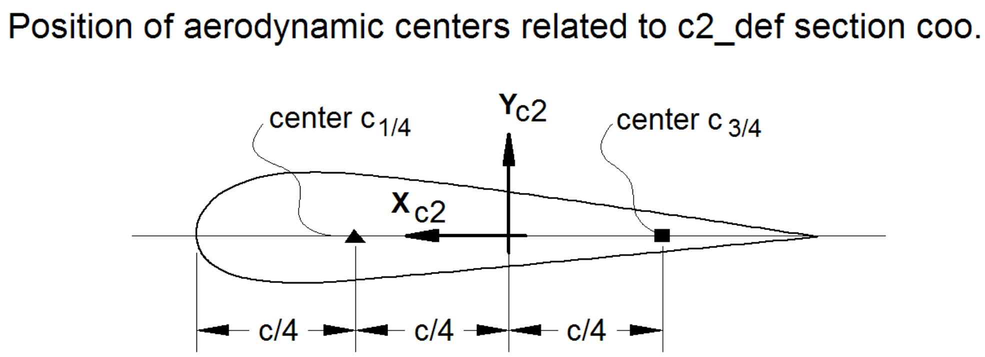


Figure 7: Illustration of aerodynamic centers $C_{1/4}$ and $C_{3/4}$

The format of the file is specified in the following two tables

Line number	Description
1	#1: Nset, Number of datasets present in the file. The format of each data set can be read below. The datasets are repeated without blank lines etc.
2	#1: Set number. #2: Nrows, Number of data rows for this set
3..2+Nrows	Data row according to Table 29

Table 28: Format of main data structure for the aerodynamic "_ae" blade layout file

The content of the colums in a data row is specified in the table below.

Column	Parameter
1	r, curved length distance from main_body node 1 [m]
2	chord length [m]
3	thickness ratio between profile height and chord [%]
4	Profile coefficient set number
(5)	Optional column. When present, it includes a dynamic stall model selector. It is then possible to bypass or change dynamic stall model for different part of the blade. Numbers are identical to the one used in the command "aero dynstall_method"

Table 29: Format of the data rows for the aerodynamic "_ae" blade layout file

12.9 Example of an aerodynamic blade layout file

```
1        Number of datasets in the file.
1 25  Set nr, nrows.
0       2.42   100    1  Radius[m]  chord[m]  thick[%]  PC [-]
1.239  2.42   100          1
1.24   2.42   99.9        1
3.12   2.48   96.4        1
5.24   2.65   80.5        1
7.24   2.81   65.0        1
9.24   2.98   51.6        1
11.24  3.14   40.3        1
13.24  3.17   32.5        1
15.24  2.99   28.4        1
17.24  2.79   25.6        1
19.24  2.58   23.7        1
```

```
20.44  2.46   22.8       1
23.24  2.21   20.9       1
25.24  2.06   20.0       1
27.24  1.92   19.4       1
29.24  1.8    19.0       1
31.24  1.68   18.7       1
33.24  1.55   18.6       1
35.24  1.41   18.3       1
37.24  1.18   17.9       1
38.24  0.98   17.3       1
39.24  0.62   16.3       1
39.64  0.48   15.7       1
40.00  0.07   14.8       1
```

12.10 Data format for the profile coefficients file

The format of this file which in the old HAWC code was known as the hawc_pc file has not been changed for the HAWC2 code.

The format of the file is specified in the following two tables

Line number	Description
1	#1: Nset, Number of datasets present in the file. The format of each data set can be read below. The datasets are repeated without blank lines etc.
2	#1: Nprofiles. Number of profiles included in the data set. There must be more than 1 Nprofiles. First profile is the thinnest, last profile is the thickest (continously increasing order).
3	#1: Profile number. #2: Nrows. #3: Thickness in percent of chord length
4..3+Nrows	Data row according to Table 31

Table 30: Format of main data structure for the profile coefficients file

The content of the columns in a data row is specified in table below.

Column	Parameter
1	α, angle of attack [deg]. Starting with -180.0, ending with +180.0
2	C_l lift coefficient [-]
3	C_d drag coefficient [-]
4	Cm moment coefficient [-]

Table 31: Format of the data rows for the profile coefficients file

12.11 Example of the profile coefficients file "_pc file"

```
1 Airfoil data for the nrel 5 mw turbine
8
1   127  17 DU17 airfoil with an aspect ratio of 17.  Original -180 to 180deg
-180.00    0.000   0.0198   0.0000
-175.00    0.374   0.0341   0.1880
-170.00    0.749   0.0955   0.3770
-160.00    0.659   0.2807   0.2747
-155.00    0.736   0.3919   0.3130
-150.00    0.783   0.5086   0.3428
-145.00    0.803   0.6267   0.3654
```

```
-140.00    0.798   0.7427   0.3820
-135.00    0.771   0.8537   0.3935
-130.00    0.724   0.9574   0.4007
-125.00    0.660   1.0519   0.4042
-120.00    0.581   1.1355   0.4047
-115.00    0.491   1.2070   0.4025
-110.00    0.390   1.2656   0.3981
-105.00    0.282   1.3104   0.3918
-100.00    0.169   1.3410   0.3838
 -95.00    0.052   1.3572   0.3743
 -90.00   -0.067   1.3587   0.3636
 -85.00   -0.184   1.3456   0.3517
 -80.00   -0.299   1.3181   0.3388
 -75.00   -0.409   1.2765   0.3248
 -70.00   -0.512   1.2212   0.3099
 -65.00   -0.606   1.1532   0.2940
 -60.00   -0.689   1.0731   0.2772
 -55.00   -0.759   0.9822   0.2595
```

12.12 Data format for the flap steady aerodynamic input (.ds file)

This file contains the pre-processed steady data required by the ATEFlap dynamic stall model. Steady lift, drag and moment coefficients are given as function of angle of attack and flap deflection, together with the fully separated and fully attached lift, and the separation function values required by the Beddoes-Leishmann dynamic stall model. The input file can be generated automatically through an external pre-processing application, as for instance the “Preprocessor for ATEFlap Dynamic Stall Model, v.2.04”. Please refer to the application documentation for further details.

The format of the file is specified in the following two tables:

Line number	Description
1	Free for comments
2	Free for comments
3	#1: Aoa0 [rad]. Angle of attack returning a null steady lift
4	Free for comments
5	#1: dCl/dAoa [1/rad]. Gradient of the steady lift function with respect to angle of attack variations
6	Free for comments
7	#1: dCl/dBeta [-]. Gradient of the steady lift function with respect to flap deflection variations
8	Free for comments
9	#1: Nrows. Total number of the following data-rows.
10...9+Nrows	Data rows, as specified in following table.

Table 32: Format of main data structure for the .ds flap steady aerodynamic input file

The content of the columns in a data row is specified in table below.

Column	Parameter
1	α, Angle Of Attack [deg]. Starting with -180.0, ending with +180.0. External loop (changes value after going through all the beta flap deflection values, i.e. 100 rows)
2	Beta, flap deflection. Starting from -49 to +50. Internal loop (changes at every data row)
3	C_l st. Steady lift coefficient [-]

Column	Parameter
4	C_l att. Fully attached lift coefficient [-]
5	C_l fs. Fully separated lift coefficient [-]
6	C_d drag coefficient [-]
7	C_m moment coefficient [-]
8	f . Steady value of the separation function [-]

Table 33: Format of the data rows for the .ds flap steady aerodynamic input file

12.13 Example of a .ds flap steady aerodynamic input file

```
Input file for Flap dyn.stall model. Generated with Delphi preprocessor
  .Linear Region: Aoa Cl0 [rad]:
-0.06523855
  .Linear Region: dCl / dAoa [1/rad]:
6.60081861
  .Linear Region: dCl / dBeta [1/deg]:
0.0435375
   . Polars: 1.Aoa | 2.Beta | 3.Clst | 4.Cl Att | 5.Cl fs | 6.Cd  | 7.Cm  | 8.F
36100
-180   -49   -0.22013   -20.5241432   -0.22013   0.0199118108   0.0451649986   0
-180   -48   -0.22013   -20.5241432   -0.22013   0.0199118108   0.0451649986   0
  ...  ...
-180   +50    0.21096   -20.088768     0.21096   0.0199443996   -0.0431930013   0
-179   -49    ...
-179   -48    ...
  ...  ...
+180   +50    ...
```

12.14 Data format for the user defined a-ct polynomial

This input file replaces the default relationship between axial induction a and rotor thrust coefficient C_T and which is expressed as a 3rd order polynomial of the following form: $a = k_3 {C_T}^3 + k_2 {C_T}^2 + k_1 C_T + k_0$. The format of the file is specified in tables 34 and 35.

Line number	Description
1. nrad interp nazi	nrad: number of radial stations (should be > 1), interp: interpolation method can only be “linear”, nazi (optional, default=1): number of azimuthal positions
2. rows	nrad*nazi number of rows according to Table 35. Group nrad rows together for each azimuthal position.

Table 34: Format of main data structure for the a-ct relation file

The azimuthal positions will be distributed equally over 360 degrees (one revolution) and start at the position corresponding to a blade pointing down (south). Other points are added in the clockwise direction. If setting 4 azimuthal position this would mean each block in the input file would correspond to first to the induction zone down (south), left (west), up (north) and finally right (east).

The content of the columns in a data row is specified in table below.

Column	Parameter
1	non-dim radius r/R
2	k_0 polynomium coef

Column	Parameter
3	k_1 polynomium coef
4	k_2 polynomium coef
5	k_3 polynomium coef

Table 35: Format of the data rows for the a-ct relation file

Here's an example with 3 radial stations and 2 different azimuthal positions (down and up):

```
3 linear 2
0.0  0.0000  0.2460  0.0586  0.0883
0.5  0.0000  0.2460  0.0586  0.0883
1.0  0.0000  0.2460  0.0586  0.0883
0.0  0.0000  0.2460  0.0586  0.0883
0.5  0.0000  0.2460  0.0586  0.0883
1.0  0.0000  0.2460  0.0586  0.0883
```

12.15 Data format for the trailing edge noise model (bldata)

This file contains the values required by the `aero_noise` module. Several different parameters are given as a function of angle of attack, relative thickness, and Reynolds number. The boundary layer data can be created from results generated with XFOIL or a CFD software such as EllipSys2D.

The format of the file is specified in the following two tables:

Line number	Description
1 – 4	Free for comments
5	#1: BLDataType [-]. Type of boundary-layer data (1=Xfoil, 2=CFD). #2: N_y [-] and number of points for BL data. N_y must be 1 for XFOIL data.
6	Free for comments
7	#1: Number of thicknesses [-].
8	Free for comments
9	#1: Relative thickness 1 [%]. First relative thickness value
10	Free for comments
11	#1: Number of Reynolds numbers at thickness 1.
12	Free for comments
13	#1: First Reynolds number at thickness 1 [-].
14	Free for comments
15	#1: Number of angles of attack for Reynolds number 1, thickness 1 [-].
16	#1: First angle of attack for for Reynolds number 1, thickness 1 [deg]
17	Data row as specified in the following table for the suction side.
18	Data row as specified in the following table for the pressure side.
19...end	Subsequent data rows and specification of other thicknesses, Reynolds numbers, and angles of attack.

Table 36: Format of main data structure for the bldata input file for trailing-edge noise model

The content of the columns in a data row is specified in table below.

Column	Parameter
1	U_e, velocity at edge of boundary layer normalized by inflow velocity U_0 [-].
2	C_f, friction coefficient [-].
3	dp/dX, pressure gradient [-].
4	δ, boundary layer thickness normalized by chord [-].
5	δ^*, boundary-layer displacement thickness normalized by chord [-].
6	θ, boundary-layer momentum thickness normalized by chord [-].
7	x_{tr}, boundary-layer transition location normalized by chord [-].
8	x_{sep}, boundary-layer separation location normalized by chord [-].
9 (CFD only)	$y_d(1)$, distance from wall for point 1 normalized by chord [-].
10 (CFD only)	$U_y(1)$, velocity at point 1 normalized by inflow velocity [-].
11 (CFD only)	$k_T(1)$, turbulence kinetic energy at point 1 normalized by U_0^2 [-].
12 (CFD only)	$\epsilon(1)$, turbulence dissipation at point 1 normalized by $\nu \cdot (U_0/c)^2$ [-], where ν is the kinematic viscosity and c is the chord.
13... (CFD only)	CFD parameters for other locations on the profile.

Table 37: Format of the data rows for the boundary layer data file for the trailing edge noise model

12.16 Example of a trailing-edge noise model file (bldata)

```
# Input (Boundary Layer) data file for aeroload_noise module in HAWC2
# Data: Uedge, Cf, dP/dX, Delta, D^star, Theta, X_tr, X_sep [All -]
#       on suct./pres. sides, Followed by ((Y,U,K_t,Epsi),1,NY) for CFD case
# BL data type (1: Xfoil - 2:CFD), NY: Nb. of points for BL data (Must be 1 for Xfoil)
 2   100
# Number of thicknesses:
  16
# New thickness no.  1
  1.3997E+01  # [% Chord] - At 1,10% Chord:     3.1352E-02  9.4569E-02 [-] ./.Chord
# Number of Reynolds numbers (at thickn.no.  1):
  13
# New Reynolds number no.  1 (t/c = 1.40E+01 [%])
  6.0000E+05  # [-]
# Number of angles of attack (at thickn.no.  1 ; at Reyn.no.  1):
  15
 -1.0000E+01  # [deg] Angle of attack no.  1 (t/c = 1.40E+01 [%] ; Reyn.= 6.00E+05 [-])
   9.7959595E-01  5.0024827E-03  1.3876976E+00  1.4695722E-02  1.9646853E-03  ...
   9.4850973E-01  3.4123155E-04 -3.2128910E-01  7.7950524E-02  3.3317935E-02  ...
  -6.0000E+00  # [deg] Angle of attack no.  2 (t/c = 1.40E+01 [%] ; Reyn.= 6.00E+05 [-])
   9.5475774E-01  3.8252693E-03  2.7709756E-01  1.9092268E-02  2.8682055E-03  ...
   9.1490195E-01  1.6144429E-03  1.4202462E-01  4.0643583E-02  1.2382229E-02  ...
  ...
...
# New thickness no. 16
  5.8782E+01  # [% Chord] - At 1,10% Chord:     1.1889E-01  3.7350E-01 [-] ./.Chord
# Number of Reynolds numbers (at thickn.no. 16):
  13
# New Reynolds number no.  1 (t/c = 5.88E+01 [%])
  6.0000E+05  # [-]
...
# New Reynolds number no. 13 (t/c = 5.88E+01 [%])
  9.0000E+06  # [-]
# Number of angles of attack (at thickn.no. 16 ; at Reyn.no. 13):
  15
...
  2.4000E+01  # [deg] Angle of attack no. 15 (t/c = 5.88E+01 [%] ; Reyn.= 9.00E+06 [-])
```

```
  1.7209753E-02  7.9763797E-04 -9.2664372E-01  3.4414559E-03  6.8894715E-03 ...
  1.2919848E+00  3.6773425E-03 -1.0974971E+01  6.3898121E-03  9.2252539E-04 ...
```

12.17 Main command block – blade_c2_def (for use with old_htc_structure format)

In this command block the definition of the centerline of the main_body is described (position of the half chord). This command shall be used as a main command even though it is only used together with the aerodynamic module. The reason for this is that it used to submit information that is usually given in the new_htc_structure format, which is also a main command block. The input data given with the sec commands below is used to define a continuous differentiable line in space using akima spline functions. This centerline is used as basis for local coordinate system definitions for sections along the structure. If a straight line is requested a minimum of three points of this line must be present.

Obl.	Command name	Explanation
*	nsec	Must be the present before a “sec” command. 1. Number of section commands given below
*	sec	Command that must be repeated “nsec” times 1. Number 2. x-pos [m] 3. y-pos [m] 4. z-pos [m] 5. θ_z [deg]. Angle between local x-axis and main_body x-axis in the main_body x-y coordinate plane. For a straight blade this angle is the aerodynamic twist. Note that the sign is positive around the z-axis, which is opposite to traditional notation for etc. a pitch angle.

12.18 Data format for the user defined a-ct table

It is possible to provide two types of tables. The first type only includes the region for positive C_T. This type of table should start from [0, 0]. Then, the relationship in the region of negative C_T is assumed to be an odd function, such that $a(-C_T) = -a(C_T)$. The second type of table includes the region of both negative and positive C_T and it is not necessary to pass through [0, 0]. The second type is recommended when modeling a rotor that might also operate as a propeller, with negative C_T.

Both types of a-ct tables need to be monotonically increasing in C_T. The tables will be linearly extrapolated outside of the range $-2.5 < C_T < 2.5$. Please ensure that the table you provide covers that range (or the range from $0 < C_T < 2.5$ if providing only a table for positive values of a and C_T). We recommend a higher resolution than in the example table below.

Line number	Description
1	Nrows, Number of data rows
2..1+Nrows	1. Axial induction factor a 2. Thrust coefficient C_T

Table 39: Format of main data structure for the user defined a_ct_table file

Example:

```
19
0.000000 0.000000
```

```
0.025274 0.100000
0.052250 0.200000
0.081458 0.300000
0.113427 0.400000
0.148688 0.500000
0.187769 0.600000
0.231201 0.700000
0.279514 0.800000
0.333237 0.900000
0.392900 1.000000
0.532166 1.200000
0.701551 1.400000
0.905293 1.600000
1.147630 1.800000
1.432800 2.000000
1.765042 2.200000
2.148595 2.400000
2.360937 2.500000
```

Additional comments for best results: We recommend a higher resolution than in this example. Further, set $a(1) = 0.0$ and $C_T(1) = 0.0$. In the table, C_T should be in increasing order: 0<= C_T(i)<C_T(i+1). The value of a and C_T should be positive except for the first row. Also provide extrapolated table until C_T=2.5.

13 Aerodrag (for tower and nacelle drag)

13.1 Main command aerodrag

With this module, it is possible to apply aerodynamic drag forces at a given number of structures.

13.2 Subcommand aerodrag_element

Command block that can be repeated as many times as needed. In this command block aerodynamic drag calculation points are set up for a given main body.

Obl.	Command name	Explanation
*	mbdy_name (old command body_name still usable)	1. Main_body name to which the aerodynamic calculation points are linked.
*	aerodrag_sections	1. Distribution method: (“uniform” only possibility) 2. Number of calculation points (min. 2).
	nsec	This command must be present before the sec commands. 1. Number of sections given below.
	sec	This command must be repeated nsec times 1. Distance in [m] along the main_body c2_def line. Positive directed from node 1 to node “last”. 2. C_d drag coefficient (default=1.0) 3. Width of structure (diameter)
	update_states	Logical parameter that determines whethe the movement of the structure is included or not. 1. parameter (1=states are updated (default), 0=not updated)

By choosing the uniform distribution, HAWC2 places n equidistant calculation points on the main body, from the first until the last node. The distributed aerodynamic drag is computed for each calculation point as

$$
\begin{aligned}
f_x &= \frac{1}{2}\rho V_x^2 c C_d \mathrm{sgn}(V_x) \\
f_y &= \frac{1}{2}\rho V_y^2 c C_d \mathrm{sgn}(V_y) \\
f_z &= 0 \\
m_x &= 0 \\
m_y &= 0 \\
m_z &= 0
\end{aligned}
$$

with ρ the air density, c the interpolated width at the calculation point and C_d the interpolated drag coefficient at the calculation point. V_x and V_y are the relative wind speed in the aerodynamic coordinate system at the calculation point, optionally including the structural one. The wind speed is evaluated only at the first iteration of each time step, while the structural one is always updated. The aerodynamic drag is not applied in the first 5 seconds of the simulation. Between 5 and 10 seconds it smoothly goes from 0 to 100%, where it remains until the end of the simulation.

14 Hydrodynamics

14.1 Main command block - hydro

In this command block hydrodynamic forces calculated using Morison's formula is set up.

14.2 Sub command block – water_properties

Obl.	Command name	Explanation
*	gravity	1. Gravity acceleration (used for calculation of buoyancy forces). Default = 9.81 $\mathrm{m/s^2}$
*	mudlevel	1. Mud level [m] in global z coordinates.
*	mwl	1. Mean water level [m] in global z coordinates.
*	rho	1. Density of the water [kg/m3]. Default=1000
	wave_direction	1. Wave direction [deg]. Direction is positive when the waves come forward from the right when looking towards the wind at default conditions.
	current	1. Current type (0=none (default), 1=constant, 2=power law $U(z) = U_0((mudlevel - mwl - z)/(mudlevel - mwl))^\alpha$ where $\alpha \geq 0$, and z refers to the water depth ranging from 0 at the surface to $mudlevel - mwl$ at the mudlevel. See also figure 8. 2. Current velocity at mwl, u_0 3. type parameter. If type=2 then parameter is α. 4. Current direction relative to wave direction [deg]. Positive direction if current comes from the right looking towards the incoming waves.
	water_kinematics_dll	1. Filename incl. relative path to file containing water kinematics dll (example ./hydro/water_kin.dll) 2. String sent to initialization of dll. This is typical the name of a local inputfile of the dll.

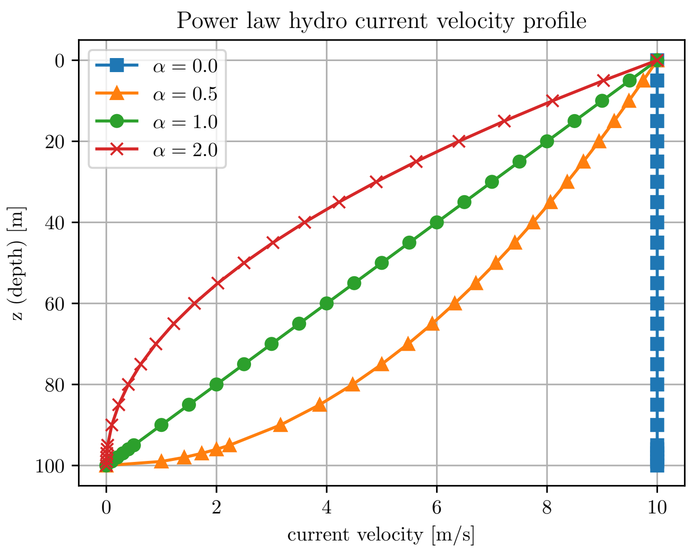


Figure 8: Hydrodynamic water current power law velocity profile for various values of α with $mwl = 0$ and $mudlevel = 100$.

14.3 Sub command block – hydro_element

Command block that can be repeated as many times as needed. This command block set up hydrodynamic calculation points and link them to a main_body.

Obl.	Command name	Explanation
*	body_name or mbdy_name	1. Main_body name to which the hydrodynamic calculation points are linked.
*	hydrosections	1. Distribution method of hydrodynamic calculation points. Options are: "uniform" nnodes. Where uniform ensures equal distance of the calculation points. nnodes are number of calculation points. "auto" nint. Here calculations points are chosen as the postions of the structural nodes and the hydro dynamic input section given by the sec command. The parameter nint is a refinement parameter given nint extra calculation points in between the other points.
*	sec_type	Type of cross section (1=circular, 2=general). Please note that sec_type should always appear before the nsec and sec commands.
	sec_length_normalized	Switch to let the hydrodynamic coordinates be read as normalized coordinates (from 0.0 to 1.0). Valid inputs are 0 to use absolute coordinates, and 1 to use normalized coordinates. By default, absolute coordinates are used. Please note that sec_length_normalized should always appear before the sec command.
*	nsec	This command must be present before the sec commands 1. Number of sections given below
*	sec	This command must be repeated nsec times and is different for each section type. **Section type 1 – circular:** 1. Coordinate along the main_body c2_def line. Positive directed from node 1 to node "last". 2. C_a added mass coefficient (default=1.0) 3. C_d drag coefficient (default=1.0) 4. Cross sectional area [m2] 5. Cross sectional area to which C_a is related. (default=area for circular sections) [m2] 6. Width of construction perpendicular to flow direction [m] 7. drdz gradient(optional). For calculating the buoyancy also for conical sections the gradient expressing the change in radius with change of distance along the main_body c2_def line. Only important when buoyancy forces are included. 8. Axial drag C_d coefficient for concentrated force contribution (optional). Drag area is circular area defined by the local width. Contribution is quadratic regarding water velocity. 9. Axial added mass $C_{a,axial}$ coefficient for concentrated force contribution (optional). Force is computed (in each hydro element section with $C_{a,axial}$ different than 0) as: $\rho V_{ref} C_{a,axial}(water\_acc - body\_acc)$, with V_{ref} taken as half volume of sphere defined by the local width as diameter. 10. Axial drag C_d coefficient for concentrated force contribution (optional). Drag area is circular area defined by the local width. Contribution is linear regarding water velocity. 11. Internal cross sectional area for flooded members [m2] (optional). 0=member is not flooded.

Obl.	Command name	Explanation
		12. Torque friction coefficient Cf (optional). For rotating cylinders around local z-direction. $M_z = \frac{1}{16}\rho\pi D^4\omega^2 \mathrm{C_f}$ 13. Magnus coefficient (optional). $F_{Magnus} = C_{Magnus}\rho V_{current} 2\pi r^2\omega$ and where r is the corresponding radius for the given cross sectional area (input 4), and C_{magnus} is the Magnus coefficient that dependends on parameters such as shape, material and flow regime (for example ratio between rotational and current velocity). **Section type 2 – general:** 1. Distance from node 1 to 2 2. Cross sectional area [m2] 3. Area radius of gyration [m] around x-axis Ri_x 4. Area radius of gyration [m] around y-axis Ri_y 5. Hydro mass coefficient in x-direction $C_{a,x}$ 6. Hydro mass coefficient in y-direction $C_{a,y}$ 7. Drag coefficient in x-direction $C_{d,x}$ 8. Drag coefficient in y-direction $C_{d,y}$ 9. Volume per length in x-direction 10. Volume per length in y-direction 11. Reference volume to which C_a is referenced 12. Reference width for C_d and $C_{a,axial}$ 13. axial drag coefficient (quadratic) $C_{d,axial,quad}$ 14. axial hydro mass coefficient $C_{a,axial}$ 15. axial drag coefficient (linear) $C_{d,axial}$
	buoyancy	1. Specification whether buoyancy forces are included or not. 0=off (default), 1=on (remember to define the 7th parameter in the sec input line.
	update_states	1. Specification whether the hydrodynamic sections are updated in time with respect to pos, vel, acc and orientations, or simply considered to remain fixed. 0=not updated, 1=updated (default)
	update_kinematics	1. Specification whether the water kinematics are updated during iterations or only once per time step. 0=only updated once per time step, 1=full update (default).

Here is an example of this written into the htc-input file.

```
begin HYDRO_ELEMENT ;
 mbdy_name cylinder ;
 buoyancy 1 ;
 update_states  1 ; (0: no dynamic interaction, 1: fully coupled solution
 hydrosections auto 4 ; dist, of hydro calculation points from 1 to nsec
 nsec 2; z   Ca Cd  A      Aref   width dr/dz Cd_a_(quad) Ca_a Cd_a_lin Aif
 sec     0.0  1  1  3.404  3.404  2.082 0.0   0.0         0.0  0.0      3.023;
 sec     5.0  1  1  3.404  3.404  2.082 0.0   0.0         0.0  0.0      3.023;
end HYDRO_ELEMENT ;
```

This example shows a flooded cylindrical element (l=5 m, d= 2,082 m and t=60mm).

14.4 Description of the water_kinematics_dll format.

```
subroutine init(inputfile,t0,t1,dt) implicit none
character*(*) :: inputfile
real*8                     :: t0        ! start time for simulation
real*8                     :: t1        ! stop time for simulation
real*8                     :: dt        ! time increment
!DEC$ ATTRIBUTES DLLEXPORT, ALIAS:'init'::init
end subroutine init

!-------------------------------------------------------------------------
subroutine set_new_time(time)
implicit none
!DEC$ ATTRIBUTES DLLEXPORT, ALIAS:'set_new_time'::set_new_time
real*8                 :: time

end subroutine set_new_time

!-------------------------------------------------------------------------
subroutine get_sea_elevation(posxy_h,elevation)
implicit none
!DEC$ ATTRIBUTES DLLEXPORT, ALIAS:'get_sea_elevation'::get_sea_elevation
real*8,dimension(2) :: posxy_h    ! horizontal position coordinates
real*8                :: elevation ! water height above mean water level, positive upwards
end subroutine get_sea_elevation

!-------------------------------------------------------------------------
!DEC$ ATTRIBUTES DLLEXPORT, ALIAS:'get_kinematics'::get_kinematics
real*8,dimension(3)  ::  pos_h, vel_h, acc_h
real*8                ::  pres
end subroutine get_kinematics
```

14.5 User manual to the standard wkin.dll version 2.8.3

The wkin.dll which is delivered along with the HAWC2 code needs a separate inputfile. The format for these inputs are the same as the HAWC2 main inputfile with usage of begin..end clauses, semi colon separators, exit command etc. Command words are described below.

All command words written below has to be included in an begin .. end clause called wkin_input:

```
begin wkin_input;
...
end wkin_input;
exit;
```

```
Version info:
 1.0 TJUL Basic edition by TJUL
 1.1 ANMH  Wave field can be read by file and used directly through fft
conversion
 1.2 TJUL Directional spreading included
 1.3 ANMH Bug corrected regarding read on seed number using iregular
waves
 1.4 TJUL Pierson-Moscowitz spectrum added as option
Stream function wave added
  Possible pre processing of wave field to speed up simulation
time and enable many more coeffients
 1.5 TJUL Bug in stream function wave. Static pressure was included -
now removed
 1.6 TJUL Bug in stream fuction wave. lateral position was applied
```

```
instead of vertical in kinematics look-up!!!
 1.7 TKIM New wave format for precalculated (high order) wave fields
 1.8 ANMH  Update in deterministic iregular waves+bugfix
 1.9 TJUL New option for white noise wave exitation
 2.0 TJUL Bug fix of version 1-9. Version 1-9 had some debug
statements included that could meas up the time.
2.1 ANMH Ported to intel
            ANMH     Correction for high wave numbers in deterministic irregular
waves
            TJUL Embedded stream function wave, phase velocity used insted
of group velocity with respect to pregenerated waves
2.2   TJUL     Bug fix. Tightended criteria for jonswap spectrup min-max.
Use of real*8 in all internal memory related variables
2.3  TJUL    Bug fix. PM spectrum ireg waves
2.4 TJUL    Update so embedded stream function wave is ensured to be inside the requested time
2.5 TJUL    Bugfix in randomnumber generator. Problem occured in version 2.1 until 2.4
SHFE    Bugfix in embedded steam function wave
2.6 TJUL    Embedded stream function wave updated for manual input of Tp
2.7 ANMH    Bugfix regarding embedded stream function wave
SHFE    Bugfix (stretching first, then embed stream function wave)
2.8 SHFE    New feature to write out the pregenerated wave field
SHFE Change PM spectra from Tz type to Tp type
SHFE Solve the memory issue when pregenerate large scale wave field
SHFE Fix issue with long filenames
2.8.3 SHFE McCamy Fuchs correction is applied on water particle acceleration
```

14.6 Main commands in the wkin.dll

Obl.	Command name	Explanation
*	wavetype	1. Type of wave used. (0=regular airy, 1=irregular airy, 2=deterministic irregular airy, 3=regular stream function, 4=general wavemode format)
*	wdepth	1. Water depth [m]. Positive value.

14.7 Sub command reg_airy

Command that need to be present if the wavetype equals 0 in the main command.

Obl.	Command name	Explanation
*	stretching	1. Wheeler stretching of waves. (0=off, 1=on)
*	wave	1. Wave height H [m] 2. Wave period T [s] 3. Wave phase shift [deg] (optional)
	ignore_water_surface	Allow the lookup of the wave kinematics above the waterline if requested in the output.

14.8 Sub command ireg_airy

Command that need to be present if the wavetype equals 1 in the main command.

Obl.	Command name	Explanation
*	stretching	1. Wheeler stretching of waves. (0=off, 1=on)

Obl.	Command name	Explanation
*	spectrum	1. Base spectrum used. (1=jonswap, 2= Pierson Moscowitz)
	mccamyfuchs	1. McCamy Fuchs correction on water particle acceleration. (0=off, 1=on) 2. Representative radius [m]
	jonswap	Jonswap spectrum formulation 1. Significant wave height H_s [m] 2. Wave period T_p [s] 3. γ parameter [-]. A typical value is 3.3
	pm	Pierson-Moscowitz spectrum 1. Significant wave height H_s [m] 2. Wave period T_p [s]
	wn	White noise. 1. Target variance level [m^2] 2. f_0, minimum frequency 3. f_1, maximumn frequency
*	coef	1. Number of coefficients. Normally 200 are used even though higher values are recommended in general. A speed issue... 2. Seed number. A positive integer value. 3. Phase shift for all wave components [deg] (optional).
	spreading	1. Spreading model. (0=none, 1=K_{2s} model also referred to as K_n model) 2. Spreading parameter. If model=1 the parameter is s, a positive integer. The higher value, the less spreading.
	pregen	Pre-generation of a wave field (default is on). Using this option the irregular wave field is calculated during initialization phase and only table look-up is done during the time simulation phase. Very fast and still accurate. 1. Pregen option. (0=traditional approach (slow), 1=pregenerated wave field used (default))
	embed_sf	Embed stream function wave in time series at the time when the otherwise largest wave occurs. The wave kinematics is blended into the iregular waves before and after. 1. Wave height H [m] 2. Wave period T [s]. Default = Peak wave period T_p. (optional) 3. Truncated transition period T0 [s]. Default = 0. (optional)

14.8.1 Sub sub command pregen_field

Command that used to define the resolution of the pregenerated wave field if this feature is activated where the pregen equals to 1 (default). The whole command block is optional.

Obl.	Command name	Explanation
	wave_filename	1. File name for writing (if file does not exist) or reading (if file exists) pregenerated wave field.
	y_resolution	1. Field dimensions in lateral direction. Default is 1. 2. Lateral grid length. Default is 0.
	t_resolution	1. The time step used for the pregenerated wave field. Default = 1/10 of maximum wave period.
	z_resolution	1. Field dimensions in vertical direction. Default is 10 points in z direction.
	x_range	1. extra simulated wave train in meters before and after requested time interval. Default is 100 m.

14.9 Sub command det_airy

Command that need to be present if the wavetype equals 2 in the main command. This command is used when water kinematics needs to be calculated based on a predetermined surface elevation time series. In the calculation of the waterkinematics, the datapoints in the input file must be equidistant in time, i.e. with a constant time-step.

Obl.	Command name	Explanation
*	file	1. File name for measured wave elevation.
*	nsamples	1. Number of lines present in wave elevation file
*	nskip	1. Number of lines to skip before reading of wave elevation file
*	columns	1. Column number for time sensor in file. 2. Column number for wave elevation in file.
	stretching	1. Wheeler stretching of waves. (0=off, 1=on (default))
*	cutoff_frac	1. Fraction of total energy which is discarded in the low and high frequency ranges. Default 1E-5
	pregen	Pre-generation of a wave field (default is on). Using this option the irregular wave field is calculated during initialization phase and only table look-up is done during the time simulation phase. Very fast and still accurate. 1. Pregen option. (0=traditional approach (slow), 1=pregenerated wave field used (default))
	x_range	1. extra simulated wave train in meters before and after requested time interval. Default is 100 m.
	wave_filename	1. File name for writing (if file does not exist) or reading (if file exists) the pregenerated wave field.

14.10 Sub command strf

Stream function wave input.

Obl.	Command name	Explanation
*	wave	1. Significant wave height H_s [m] 2. Wave period T [s] 3. Current speed U [m/s]

14.11 Sub command wavemods

Command that need to be present if the wavetype equals 4 in the main command. This command is used when water kinematics are supplied directly to HAWC2 from input files.

Obl.	Command name	Explanation
*	datafile_y	1. Name of datafile where wave kinematic data is present for the horizontal (wave) direction
*	datafile_z	1. Name of datafile where wave kinematic data is present for the vertical direction
*	datafile_nd	1. Number of depth locations
*	datafile_depth	1. Maximum water depth (m)
*	datafile_nt	1. Number of time steps in datafile
*	datafile_t0	1. Time for when wave data is extracted in the datafiles
*	ncol_y	1. Number of columns in datafile1 (time + eta + nd*(vel+acc))
*	ncol_z	2. Number of columns in datafile2 (time + nd*(vel+acc))

An example of input files with wave kinematics data for the wavemods option is given below. Please note the following:

- The first 9 lines are general comment lines
- Line 10 lists the position at which the velocities and accelerations are applied in non-dimensional coordinate σ. σ is 0 at the mudlevel, and 1 at the instantaneous free surface (mwl + eta). The number of coordinates must match datafile_Nd in the wavemods subcommand. The coordinates must be given in ascending order, i.e. from 0 to 1.
- Each row starting at Line 12 corresponds to a single time step, and there should be at least datafile_Nt rows before the end of the file
- The datafile columns correspond to time, eta (the distance between the wave height and the MSL; not present in the vertical-component input file), datafile_Nd velocities, and then datafile_Nd accelerations

Example of datafile_y (horizontal wave component):

```
1  Wave kinematics input to Flex5 Monopile ver. 2.1
2  General comment line
3  Wave load program "WaveKin" ver. 1.0
4  Echo file : Outfile.dat
5  Name of Case
6  Wave Description
7  slope 1:25
8  50  water depth
9   3 No rel. depths N
10 0.000        0.500        1.000
11  T      eta   u[1]..u[N]     a[1]..a[N]
12 0.000         -0.645         -0.022         -0.027         -0.047
   ↪  -0.018         -0.022         -0.035
13 0.063         -0.659         -0.023         -0.029         -0.049
   ↪  -0.017         -0.021         -0.032
14 0.126         -0.671         -0.025         -0.030         -0.051
   ↪  -0.016         -0.020         -0.030
15 ...
```

Example of datafile_z (vertical wave component):

```
1  Wave kinematics input to Flex5 Monopile ver. 2.1
2  General comment line
3  Wave load program "WaveKin" ver. 1.0
4  Echo file : Outfile.dat
5  Name of Case
6  Wave Description
7  slope 1:25
8  50  water depth
9   3 No rel. depths N
10 0.000        0.500        1.000
11  T      u[1]..u[N]     a[1]..a[N]
12 0.000         -0.022         -0.027         -0.047         -0.018
   ↪  -0.022         -0.035
13 0.063         -0.023         -0.029         -0.049         -0.017
   ↪  -0.021         -0.032
14 0.126         -0.025         -0.030         -0.051         -0.016
   ↪  -0.020         -0.030
15 ...
```

14.12 Wkin.dll example file

```
begin wkin_input ;
  wavetype 1 ;       0=regular, 1=irregular, 2=deterministic
  wdepth  220.0 ;
;
  begin reg_airy ;
    stretching 0;    0=none, 1=wheeler
    wave 9 12.6;     Hs,T
  end;
;
  begin ireg_airy ;
    stretching 0;     0=none, 1=wheeler
    spectrum   1;    (1=jonswap)
    jonswap 9 12.6 3.3 ; (Hs, Tp, gamma)
    coef 200 1 ;      (coefnr, seed)
    spreading 1 2;      (type(0=off 1=on), s parameter (pos. integer min 1)
  end;
;
  begin det_airy ;
    stretching 0;     0=none, 1=wheeler
    file ..\waves\elevation.dat ;
    nsamples 32768 ;
    nskip 1 ;
    columns 1 5 ;     time column, elevation column
  end;
;
  begin wavemods;
    datafile_y  ./wavedata/wavekin_y.dat;
    datafile_z  ./wavedata/wavekin_z.dat;
    datafile_nt  900;  number of time steps in file
    datafile_nd  3;  number of relative water depths
    datafile_t0  50;   start time for data extraction
    datafile_depth  50 ; minimum water depth
    ncol_y 8; Number of data columns in file
    ncol_z 7; Number of data columns in file
  end;
end;
;
exit ;
```

15 Soil module

15.1 Main command block - soil

In this command block soil spring/damper forces can be attached to a main body. The formulation is performed so it can be used for other external distributed spring/damper systems than soil.

15.2 Sub command block – soil_element

Command block that can be repeated as many times as needed. In this command block the distributed soil spring/damper system is set up for a given main body.

Obl.	Command name	Explanation
*	mbdy_name	1. Main_body name to which the soil calculation points are linked.
*	datafile	1. Filename incl. relative path to file containing soil spring properties (example ./soil/soildata.dat)
*	soilsections	1. Distribution method: ("uniform" only possibility) 2. Number of section (min. 2).
	damping_k_factor	1. Rayleigh kind of damping. Factor the linear stiffness coefficients are multiplied with to obtain the damping coefficients. When the factor is 1.0 the vibration is critically damped for the rigid mainbody connected to the spring and dampers.
♣	set	1. Set number in datafile that is used.

*) Input commands that must be present

♣) Command can be repeated as many times as desired.

15.3 Data format of the soil spring datafile

In the file (which is a text file) different distributed springs can be defined. Each set is located after the "#" sign followed by the set number. Within a set the following data needs to be present.

line 1	"spring type"	(can be "axial", "lateral" or "rotation_z")
line 2	"nrow ndefl"	(nrow is number of rows, ndefl is number of deflections (colums)
line 3.. 3+nrow	"z_global F(1) F(2),..., F(ndefl)"	First colum is the spring location (global z coordinate). The following colums are Force/length at the different deflection stations. First deflection must be zero. The forces are assumed symmetrical around the zero deflection.

An example is given below:

```
This is a nonlinear soil spring demonstration file
#1
lateral              (axial/lateral)
5 4                          nrow ndefl
        0.0         0.1         0.2         1.0   x1 x2 x3 .....         [m]
0.0          0          15          20          500   Z_G  F_1 F_2 F_3 .... F_ndefl [kN/m]
10.0         0          15          20          500
20.0         0          15          20          500
```

```
30.0         0          15          20          500
40.0         0          15          20          500
#2
axial                (axial/lateral)
5 4                        nrow ndefl
        0.0         0.1         0.2         1.0   x1 x2 x3 .....        [m]
0.0          0          150         200         5000  Z_G  F_1 F_2 F_3 .... F_ndefl [kN/m]
10.0         0          150         200         5000
20.0         0          150         200         5000
30.0         0          150         200         5000
40.0         0          150         200         5000
#3
rotation_z           (axial/lateral/rotation_z)
5 4                        nrow ndefl
        0.0         0.1         0.2         1.0   x1 x2 x3 .....        [rad]
0.0          0          150         200         5000  Z_G M_1 M_2 M_3 .... M_ndefl [kNm/m]
10.0         0          150         200         5000
20.0         0          150         200         5000
30.0         0          150         200         5000
40.0         0          150         200         5000
```

16 External forces

16.1 Main command block – Force

16.1.1 Sub command - Base

This command block can be used to specify a user-defined constant external force and/or moment on a node on the structure.

Obl.	Command name	Explanation and parameters
	name	1. Name used to reference the force DLL from output sensors.
	mbdy	1. Name of mainbody.
	node	1. Node number.
	force	External force in global coordinates 1. Fx [N] 1. Fy [N] 1. Fz [N]
	moment	External moment in global coordinates 1. Mx [Nm] 1. My [Nm] 1. Mz [Nm]

16.1.2 Sub command - DLL

This command block can be used when a user defined external force is applied to the structure. The main difference between this DLL format and the normal DLL control interface (used with external controllers) is that added stiffness is calculated initially leading to a more robust a fast solution of the coupled system. This force module can with good results be applied for external equivalent soil-springs or hydrodynamic forces for floating constructions or mooring lines.

Obl.	Command name	Explanation and parameters
	name	1. Name used to reference the force DLL from output sensors.
*	filename	1. Filename incl. relative path to the external DLL (example ./dll/force.dll)
	dll	deprecated alternative to filename
	init	1. Name of subroutine in the DLL that is called before the simulation starts. 2. String passed to the init subroutine.
*	update	1. Name of subroutine in the DLL that is called at each time step to provide the forces and moments.
	output	1. Name of subroutine in the DLL that is called at each time step to send the DLL output in the HAWC2 results file.
	output_label	1. Name of subroutine in the DLL that is called at the beginning of the simulation to label the output channels. Requires the “output” command.
*	mbdy	1. Name of main body to which force DLL is coupled.
*	node	1. Node number of main body to which this force DLL is coupled.

16.2 Example of a DLL interface written in fortran90

```
!
! Demonstration of force DLL
```

```
!
SUBROUTINE DemoForceDLL(time,x,xdot,xdot2,amat,omega,omegadot,F,M)
!DEC$ ATTRIBUTES DLLEXPORT::DemoForceDLL
!DEC$ ATTRIBUTES ALIAS:'demoforcedll' :: DemoForceDLL
! input
DOUBLE PRECISION                  :: time     ! time
DOUBLE PRECISION ,DIMENSION(3)    :: x               ! global pos. of reference node
DOUBLE PRECISION ,DIMENSION(3)    :: xdot     ! global vel. of reference node
DOUBLE PRECISION ,DIMENSION(3)    :: xdot2    ! global acc. of reference node
DOUBLE PRECISION ,DIMENSION(3)    :: omega    ! angular vel. of ref. node
                                              ! (global base)
DOUBLE PRECISION ,DIMENSION(3)    :: omegadot ! angular acc. of ref. node
                                                ! (global base)
DOUBLE PRECISION ,DIMENSION(3,3) :: amat      ! rotation matrix (body ->
                                                !                   global)
! output
DOUBLE PRECISION ,DIMENSION(3)    :: F         ! External force in reference
                                                ! node (global base)
DOUBLE PRECISION ,DIMENSION(3)    :: M         ! External moment in reference
                                                ! node (global base)
! locals
LOGICAL, SAVE                     :: bInit = .FALSE. ! Initialization flag
DOUBLE PRECISION                  :: mass  = 0.d0    ! Point mass
!
! Initialise on first call
IF (.NOT.bInit) THEN
  bInit = .TRUE.
  ! Open file and read mass
  OPEN(10,FILE="DemoForceDLL_mass.dat")
  READ(10,*) mass
  CLOSE(10)
ENDIF
!
! Calc. force
F = mass*((/0.d0,0.d0,9.81d0/) - xdot2)
M = 0.d0
!
END SUBROUTINE DemoForceDLL
```

16.3 Example of a DLL interface written in Lazarus / Pascal

```
library force_dll;

Type
  vect = array[0..2] of double;
  mat  = array[0..2,0..2] of double;

procedure update(var time:double;var x:vect;var xdot:vect;var xdot2:vect;
            var amat:mat;var omega:mat;var omegadot:vect;
            var F,M:vect);stdcall;

// Example of applying a step up force in the x-direction:
begin
if time < 10 then
  F[0] := 0.0;
if time >= 10 then
  F[0] := 20000.0;
if time >= 20 then
  F[0] := 40000.0;
end;

exports update;

```

```
begin
  writeln('The DLL force_dll.dll is loaded with succes');
end.
```

17 Output

This command output can either be a main command block or a sub command block within the `hawc_dll` and `type2_dll` command blocks. In the tables below two special columns are introduced. One is only option and the other label option.

17.1 Only option

When the check mark is 'yes' in only option it is possible to use only one of the fields if more than one sensor was defined through the command. The sensor that is used is determined by the number following the only command word, see example below.

```
constraint bearing1 shaft_rot 2 only 2;
```

If the only command (and the following number) was omitted two sensors was defined; one for the angle and one for the velocity. With the only command only the velocity sensor is used in the output since the following number is 2.

17.2 Label option

When the check mark is 'yes' in only label it is possible to specify a label that is appended to the sensor description in the sensor list file. Normal text after the # symbol is used as a label. An example of this could be

```
dll inpvec 1 1 # This is a dummy label;
```

In this example the sensor description will be:

```
DLL : 1 inpvec : 1 This is a dummy label
```

17.3 Custom sensor name, unit and description

It is also possible to overwrite the name, unit and description of a sensor. This option applies to all sensors. Names, units and descriptions are specified using the using the *$name()*, *$unit()* and *$desc()* options, which must be placed after the output line, either before or after the # symbol, e.g.:

```
dll inpvec 1 1 # $name(MySensorName) $unit(MySensorUnit) $desc(MySensorDescription);
```

17.4 Derived sensors

With the *$calc()* option, the output value of output sensors can be manipulated by various math operations. This feature can be used e.g. to offset time sensor, or to scale forces from kN to N, or to do more complex operations. The $calc() must be placed after the output line, either before or after the # symbol, e.g.

```
dll inpvec 1 1 $calc(*1000) # This is a dummy label;
```

The operation string inside $calc() is composed of sets of:

1. Operation key describing the math operation (e.g. '-','+','*','/'),
2. then a (optional, dependent on operation) number <val>,
3. and then '=' character (to separate operations)(this can be omitted for last operation)

E.g. $calc(-100=*5) added to sensor line x will return (x-100)*5 in the x sensor output.

Other math operations available (other than -+*/) are:

power,	$calc(pow<val>)	:	returns $x^{<val>}$
signed power,	$calc(sgnpow<val>)	:	returns sign(x) * abs($x^{<val>}$)
absolute,	$calc(abs)	:	returns abs(x)
sine,	$calc(sin)	:	returns sin(x)
cosine,	$calc(cos)	:	returns cos(x)
tangens,	$calc(tan)	:	returns tan(x)

17.5 Commands used with results file writing

When the output command is used for output files (the most normal purpose) some information regarding file name and format needs to be given.

Obl	Command	Explanation
*	filename	1. Filename incl. relative path to outputfile without extension (example ./res/output)
	data_format	ASCII or compressed binary output can be chosen. Default is the ASCII format if nothing is specified. 1. format ('hawc_ascii'=ASCII format, 'hawc_binary'=compressed binary format, 'flex_int'=compressed binary format, 'gtsdf'=General time series data format (hdf5 based compressed binary), 'gtsdf64'=General time series data format (hdf5 based binary)) 2. optional for 'flex_int', time [s] to subtract from the time channel.
	buffer	Buffer size in terms of time steps. When the buffer is full the data are written to data file. Only used together with the 'hawc_ascii',' gtsdf' and 'gtsdf64' formats. Default is 3000 time steps 1. 1. buffer size
	deltat	Time interval between outputs [s]. If 'deltat' is smaller than simulation time step, output is made each time step.
	time	Time start t_0 and stop t_1 for output is defined. Default is the entire simulation length if nothing is specified. 2. t_0 3. t_1

17.6 File format of HAWC_ASCII files

Results are written to an ascii formatted data file with the name assigned to the filename variable (eg. filename ./res/resfil). The data file will have the extension .dat as a standard. The description of the sensors in the data file is given in another textfile with same filename as the data file but the extension .sel. An example could be: ./res/resfil.dat and ./res/resfil.sel.

In the .sel-file, line numer 9 specifies the following parameters: Number of scans, Number of sensors, Duration of output file, Data format (ASCII/BINARY). Example:

```
10 96 20.000 ASCII
```

From line number 13 and onwards, the sensors are specified with the following information: Sensor number, Variable description, unit, Long description. Example:

```
5      bea1 angle_speed               rad/s      pitch1 angle speed
```

Full example of the .sel file:

```
1  ____________________________________________________________________________
2    Version ID : HAWC2MB 4.3w
3                                                            Time : 14:23:28
4                                                            Date : 22:11.2006
5  ____________________________________________________________________________
6    Result file : ./res2_rev0/case41c_nohydro.dat
7  ____________________________________________________________________________
8     Scans    Channels    Time [sec]      Format
9       4500      199         90.000       ASCII
10
11   Channel   Variable Description
12
13      1      Time                          s          Time
14      2      bea1 angle                    deg        shaft_rot angle
15      3      bea1 angle_speed              rpm        shaft_rot angle speed
16      4      bea1 angle                    deg        pitch1 angle
17      5      bea1 angle_speed              rad/s      pitch1 angle speed
18      6      bea1 angle                    deg        pitch2 angle
19      7      bea1 angle_speed              rad/s      pitch2 angle speed
20      8      bea1 angle                    deg        pitch3 angle
21      9      bea1 angle_speed              rad/s      pitch3 angle speed
22 ____________________________________________________________________________
```

17.7 File format of HAWC_BINARY files

In this file format results are written to a binary unformatted data file with the name assigned to the filename variable (eg. filename ./res/resfil). The data file will have the extension .dat as a standard. The description of the sensors in the data file is given in another textfile with same filename as the data file but the extension .sel. An example could be: ./res/resfil.dat and ./res/resfil.sel.

The data are scaled to standard 2-byte integers, with a range of 32000 using a scalefactor. The scalefactor is determined for each output sensor

$$s = \frac{\max(|max|, |min|)}{32000}$$

where *max* and *min* are the largest and lowest number in the original data for the sensor. These scale factors are written in the end of the accompanying .sel file. When converting a binary number to the actual number its just a matter of multiplying the binary numbers of a sensor with the corresponding scalefactor.

In the accompanying text file, which has the extension .sel-file, information of the content in the datafile is stored. In line number 9 the following parameters are specified: Number of scans, Number of sensors, Duration of output file, Data format (ASCII/BINARY). Example:

```
10 96 20.000 ASCII
```

From line number 13 and onwards, the sensors are specified with the following information: Sensor number, Variable description, unit, Long description. Example:

```
5      bea1 angle_speed               rad/s      pitch1 angle speed
```

From line number 9+nsensors+5 and upwards the scalefactors are written.

Full example of the .sel file:

```
_____________________________________________________________________________
  Version ID : HAWC2MB 4.3
                                                         Time : 14:23:28
                                                         Date : 22:11.2006
_____________________________________________________________________________
  Result file : ./res2_rev0/case41c_nohydro.dat
_____________________________________________________________________________
   Scans    Channels    Time [sec]      Format
     4500        9         90.000       ASCII

  Channel   Variable Description

     1      Time                          s          Time
     2      bea1 angle                    deg        shaft_rot angle
     3      bea1 angle_speed              rpm        shaft_rot angle speed
     4      bea1 angle                    deg        pitch1 angle
     5      bea1 angle_speed              rad/s      pitch1 angle speed
     6      bea1 angle                    deg        pitch2 angle
     7      bea1 angle_speed              rad/s      pitch2 angle speed
     8      bea1 angle                    deg        pitch3 angle
     9      bea1 angle_speed              rad/s      pitch3 angle speed
_____________________________________________________________________________
Scale factors:
  1.56250E-04
  5.61731E-03
  4.41991E-04
  1.00000E+00
  1.00000E+00
  1.00000E+00
  1.00000E+00
  1.00000E+00
  1.00000E+00
```

An important thing to notice is that in the binary data file all sensors are stored sequentially, i.e. all data for sensor 1, all data for sensor 2, etc. This way of storing the data makes later reading of a sensor extra fast since all data for a sensor can be read without reading any data for the other sensor.

A small matlab code for reading the binary HAWC2 format can be seen below.

```
function sig = ReadHawc2Bin(FileName,path);
% Reads binary HAWC2 results file
% -------------------------------------
% [t,sig] = ReadFlex4(FileName,Ch);
% filename should be without extension
% -------------------------------------
% BSKA 26/2-2008
% --------------------------------------
ThisPath = pwd; cd(path(1,:))

% reading scale factors from *.sel file
fid = fopen([FileName,'.sel'], 'r'); fgets(fid); fgets(fid);
fgets(fid); fgets(fid); fgets(fid); fgets(fid); fgets(fid);
fgets(fid);
tline = fscanf(fid,'%d');
N = tline(1); Nch = tline(2); Time = tline(3); fclose(fid);
ScaleFactor = dlmread([FileName,'.sel'],'',[9+Nch+5 0 9+2*Nch+4
0]);

% reading binary data file
fid = fopen([FileName,'.dat'], 'r'); sig =
fread(fid,[N,Nch],'int16')*diag(ScaleFactor); fclose(fid);

```

```
cd(ThisPath)
```

17.8 File format for gtsdf and gtsdf64 files

The file formats and reading and writing examples of the gtsdf and gtsdf64 file types and are described here: `https://gitlab.windenergy.dtu.dk/toolbox/WindEnergyToolbox/blob/master/wetb/gtsdf/General%20Time%20Series%20Data%20Format.pdf`

A reference Python implementation to read and write gtsdf files is available in the open source Wind Energy Toolbox: `https://gitlab.windenergy.dtu.dk/toolbox/WindEnergyToolbox/blob/master/wetb/gtsdf/gtsdf.py`

17.9 Hub- and nacelle-lidar sensors

The hub- and nacelle-lidar sensors are single-beam lidars that were implemented and updated, respectively, in HAWC2 version 13.1 (see [20]). Both sensors take into account tower motion when calculating the line-of-sight velocities.

The nacelle-lidar sensor is a continuous-wave (CW) lidar, which can be offset from the rotor to a desired initial position. The hub-lidar sensor is a pulsed lidar and is positioned at the rotor center, but rotates with the rotor. Both sensors translate and rotate with the nacelle. In addition to the weighted line-of-sight velocity, the outputs of the hub lidar sensor include the line-of-sight velocity without weighting as well as the three turbulence components at the measurement point. For more details on the two lidar sensors, please read [20].

17.10 mbdy (main body output commands)

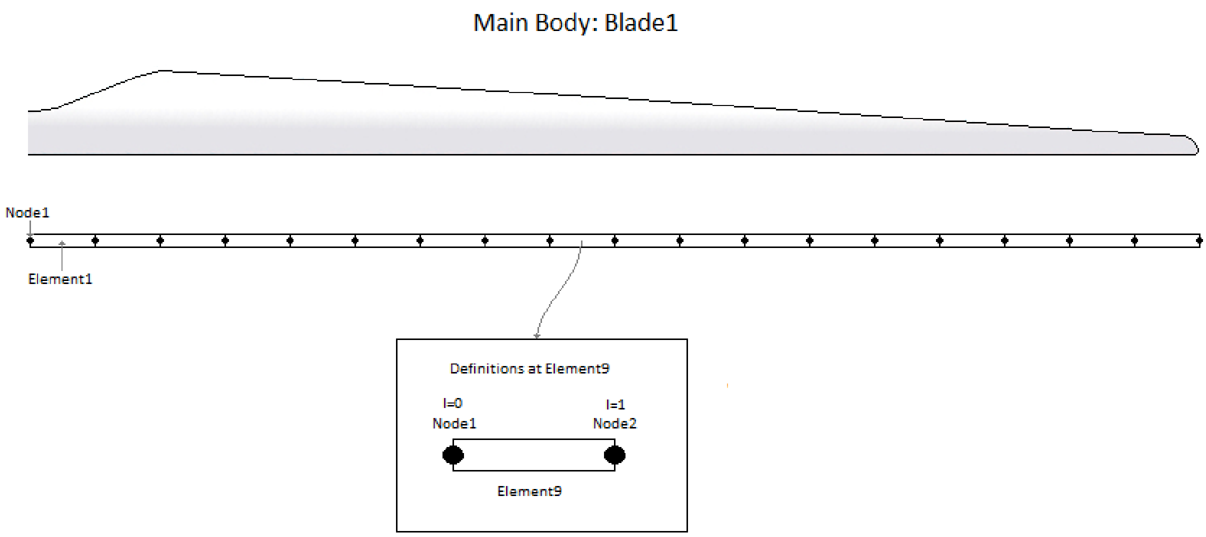
Command 1	Command 2	Explanation	Only option	Label option
mbdy	forcevec	F_x, F_y, F_z shear force vector, see definition in figure 9. 1. Main_body name 2. Element number 3. Node number on element (1 or 2) 4. Main_body name of which coordinate system is used for output. “global” and “local” can also be used. Local is around local beam main bending directions.	yes	yes
mbdy	momentvec	M_x, M_y, M_z moment vector, see definition in figure 9. 1. Main_body name 2. Element number 3. Node number on element (1 or 2) 4. Main_body name of which coordinate system is used for output. “global” and “local” can also be used. Local is around local beam main bending directions.	yes	yes

Command 1	Command 2	Explanation	Only option	Label option
mbdy	forcemomentvec_interp	F_x, F_y, F_z, M_x, M_y, M_z interpolated shear force and moment vector defined to output. This sensor can write out an interpolated set of cross sectional forces and moments independent of the node discretization. It can also write out in local deformed c2_def coordinates and therefore breaks the limit of using element coordinates. 1. Main_body name 2. Position of location outputted: 'c2def' or 'default' (default = elastic center). 3. Name of mbdy used for output coordinate system: mbdy_name, 'global', 'local_aero' or 'local_element' 4. Distance along c2_def to output location 5. Sign multiplied to output: 1.0 or -1.0	yes	yes
mbdy	state	Vector with 3 components of either position, velocity or acceleration of a point on an element defined to output. If 'acg' is used, the acceleration including the gravity contribution is written. 1. State: 'pos', 'vel', 'acc', 'acg' ("pos"=position, "vel"=velocity, "acc"=acceleration) 2. Main_body name 3. Element number 4. Relative distance from node 1 to node 2 on element 5. Main_body name of which coordinate system is used for output. "global" can also be used.	yes	yes
mbdy	state_at	Vector with 3 components of either position, velocity or acceleration of a point on an element defined to output. The point is offset from the element z axis by an x and y distance in element coordinates. 1. State: 'pos', 'vel', 'acc', 'acg' 2. Main_body name 3. Element number 4. Relative distance from node 1 to node 2 on element 5. Main_body name of which coordinate system is used for output. "global" can also be used. 6. x-coordinate offset [m] 7. y-coordinate offset [m]	yes	Yes
mbdy	state_at2	Vector with 3 components of either position, velocity or acceleration of a point on an element defined to output. The point is offset from the c2_def centerline z axis by an x and y distance in local c2def centerline coordinates. 1. State: 'pos', 'vel', 'acc', 'acg' 2. Main_body name 3. Element number 4. Relative distance from node 1 to node 2 on element	yes	Yes

Command 1	Command 2	Explanation	Only option	Label option
		5. Main_body name of which coordinate system is used for output. “global” can also be used. 6. x-coordinate offset [m] 7. y-coordinate offset [m]		
mbdy	state_rot	Vector with components of either axis and angle (angle [rad], r_1,r_2,r_3), euler parameters (quaternions r_0,r_1,r_2,r_3), euler angles, rotation velocity (-vector) or rotation acceleration (-vector) of a point on an element defined to output. For the sensor eulerang_xyx a set of euler angles are created based on the orientation matrix. Be aware that the method used is only valid for rotations in the intervals (θ_x ±180°, θ_y ±90°, θ_x ±180°). The method proj_ang can be used to see how much a blade tip rotates around the pitch axis, but be aware that the angles are how the element is oriented and not necesarily how the local chord is rotated. With the command proj_ang the angles are obtained from the local element orientation 3x3 matrix T_e, seen from the chosen coordinate system using the Atan2 functions (rot_x=atan2[T_e(2,3),T_e(3,3)], rot_y=atan2[T_e(3,1),T_e(1,1)], rot_z=atan2[T_e(1,2),T_e(2,2)]). 1. State : ’axisangle’, ’eulerp’, ’eulerang_xyz’, ’omega’, ’omegadot’ or proj_ang 2. Main_body name 3. Element number 4. Relative distance from node 1 to node 2 on element 5. Main_body name of which coordinate system is used for output. “global” can also be used.	yes	Yes
mbdy	statevec_new	This sensor writes out the position vector and orientation vector for a point on the structure. The orientation vector is a direction vector to which the structure is rotated and the vector length is the size of this rotation. There is a direct relation between this vector and the 3x3-orientation matrix, but it is easier to overview as each single element corresponds to a 2D projected rotation (rot_x, rot_y, rot_z). Furthermore it can write out the orientation of the local deformed c2_def coordinates system and therefore breaks the limit of only looking at element orientations. 1. Main_body name 2. Position of location outputted: ’c2def’ or ’default’ (default = elastic center). 3. Name of mbdy used for output coordinate system: mbdy_name or ’global’	yes	Yes

Command 1	Command 2	Explanation	Only option	Label option
		4. State: 'elastic' or 'absolute'. Elastic means that initial location is subtracted results 5. Distance along c2_def to output location 6. Sign multiplied to output: 1.0 or -1.0 7. x-coordinate offset from center to a point where location is outputted (local c2def coo) [m] 8. y-coordinate offset from center to a point where location is outputted (local c2def coo) [m]		
mbdy	wind	This sensor writes out the global or relative wind velocity components for a point on a main body. The measurement point follows the structure rigid body motions and elastic deflections. This output channel can be important if the wind measurement point moves long distances during the analysis. For example floating wind turbines can move dozens meters during a simulation. 1. Main_body name 2. Element number on the main body 3. Relative distance from node 1 to node 2 on the element 4. Wind velocity measurement method: 'global' or 'relative'. Relative means the point velocity is substracted from the global wind speed 5. x-coordinate offset of the point [m] 6. y-coordinate offset of the point [m]	yes	Yes

This illustration shows how the sensors are placed on an element in terms of local nodes and relative distance.



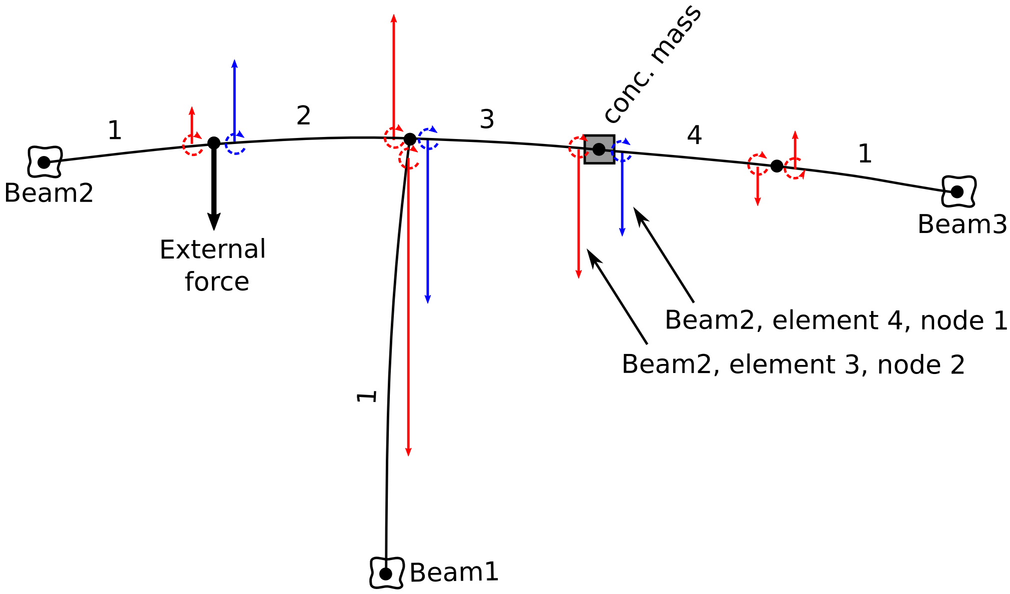


Figure 9: The "mbdy forcevec" and "mbdy momentvec" sensor definitions depend on argument 3, "node number on element", which must be 1 or 2.
For node number 1 (element start node), the sensors output the forces and moments (blue in figure) that the element and the succeeding structure (excluding concentrated masses and external forces attached to the node) applies to the preceding structure.
For node number 2 (element end node), the sensors output the forces and moments (red in figure) that the succeeding structure (including concentrated masses and external forces attached to the node) applies to the element and the preceding structure.

17.11 Constraint (constraint output commands)

17.11.1 bearing1

Command 1	Command 2	Explanation	Only option	Label option
constraint	bearing1	Bearing angle and angle velocity defined to output 1. bearing1 name 2. unit of output (1:angle [unit=rad, range -π:π], vel [rad/s]; 2:angle [unit=deg, range 0:360], vel [rpm]; 3:angle [unit=deg, range 0:360], vel [rad/s]); 4:angle [unit=deg, range -180:180], vel [rad/s]; 5:angle [unit=deg, range -180:180], vel [deg/s])	Yes	No

17.11.2 bearing2

Command 1	Command 2	Explanation	Only option	Label option
constraint	bearing2	Bearing angle and angle velocity defined to output 1. bearing2 name 2. unit of output (1:angle [unit=rad, range -π:π], vel [rad/s]; 2:angle [unit=deg, range 0:360], vel [rpm]; 3:angle [unit=deg, range 0:360], vel [rad/s]); 4:angle [unit=deg, range -180:180], vel [rad/s]; 5:angle [unit=deg, range -180:180], vel [deg/s])	Yes	No

17.11.3 bearing3

Command 1	Command 2	Explanation	Only option	Label option
constraint	bearing3	Bearing angle and angle velocity defined to output 1. bearing3 name 2. unit of output (1:angle [unit=rad, range -π:π], vel [rad/s]; 2:angle [unit=deg, range 0:360], vel [rpm]; 3:angle [unit=deg, range 0:360], vel [rad/s]); 4:angle [unit=deg, range -180:180], vel [rad/s]; 5:angle [unit=deg, range -180:180], vel [deg/s])	Yes	No

17.11.4 bearing4

Rotation angle and velocity of the two axis perpendicular to the cardan shaft torsion axis are outputted.

Command 1	Command 2	Explanation	Only option	Label option
constraint	bearing4	Bearing angle and angle velocity defined to output 1. bearing4 name 2. unit of output (1:angle [unit=rad, range -π:π], vel [rad/s]; 2:angle [unit=deg, range 0:360], vel [rpm];	Yes	No

Command 1	Command 2	Explanation	Only option	Label option
		3:angle [unit=deg, range 0:360], vel [rad/s]); 4:angle [unit=deg, range -180:180], vel [rad/s]; 5:angle [unit=deg, range -180:180], vel [deg/s])		

17.12 aero (aerodynamic related commands)

Command 1	Command 2	Explanation	Label option
aero	time	Simulation time to output. No parameters.	No
aero	azimuth	Azimuth angle of selected blade. Zero is vertical downwards. Positive clockwise around blade root y-axis. (For VAWTs, the definition is different and is computed according to the global coordinate system. When seen from above, the wind is coming from the west, blowing towards the east along the global y-axis if there is no wind "yaw". The azimuthal angle is zero when the blade is at the south, increasing in the clockwise direction.) Unit [deg] 1. Blade number	No
aero	omega	Rotational speed of rotor. Unit [rad/s]. See additional explanations below table.	No
aero	vrel	Relative velocity in x-y local aerodynamic plane. Unit [m/s] 1. Blade number 2. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	vrel_3d	Relative velocity in x-y-z local aerodynamic space. Unit [m/s] 3. Blade number 4. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	alfa	Angle of attack in x-y local aerodynamic plane. Unit [deg] 1. Blade number 2. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	alfadot	Pitch rate term (z-axis rotation) in local aerodynamic plane, as used for non-circulatory contributions. Unit [rad/s] 1. Blade number 2. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	sideslip	Side slip angle (from radial flow of BEM expansion) 1. Blade number 2. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	beta	Flap deflection angle (matching the deflection specified by the flap control .dll): 1. Blade number	No

Command 1	Command 2	Explanation	Label option
		2. Flap number, according to the order defined in the dynstall_ateflap sub-command block.	
aero	cl	Instantaneous lift coefficient. Unit [-] 1. Blade number 2. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	cd	Instantaneous drag coefficient. Unit [-] 1. Blade number 2. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	cm	Instantaneous moment coefficient. Unit [-] 1. Blade number 2. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	lift	Lift force at calculation point. Unit [kN/m] 1. Blade number 2. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	drag	Drag force at calculation point. Unit [kN/m] 1. Blade number 2. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	moment	Aerodynamic moment at calculation point. Unit [kNm/m] 1. Blade number 2. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	secforce	Aerodynamic force at calculation point. Local aero coo. Unit [kN/m] 1. Blade number 2. Dof number (1=F_x, 2=F_y, 3=F_z) 3. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used) 4. Coordinate system (1=aero, 2=blade, 3=global, 4=rotor polar) Note that 4th input argument is optional (default=1)	No
aero	secmoment	Sectional aerodynamic moment. Unit [kNm/m] 1. Blade number 2. Dof number (1=M_x, 2=M_y, 3=M_z) 3. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used) 4. Coordinate system (1=aero, 2=blade, 3=global, 4=rotor polar) 5. Dimensionless position on the chord where the moment is calculated (0= leading edge, 1= trailing edge) Note that 4th input argument (default=1) and the 5th input argument (default=0.75) are optional	No
aero	int_force	Integrated aerodynamic forces from tip to calculation point. NB the integration is performed around the $C_{3/4}$ location. Unit [kN]	No

Command 1	Command 2	Explanation	Label option
		1. Coordinates system (1=local aero coo, 2=blade ref. system, 3=global, 4=rotor polar) 2. Blade number 3. Dof number (1=F_x, 2=F_y, 3=F_z) 4. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	
aero	int_moment	Integrated aerodynamic moment from tip to calculation point. NB the integration is performed around the $C_{3/4}$ location. Unit [kNm] 1. Coordinates system (1=local aero coo, 2=blade ref. system, 3=global, 4=rotor polar) 2. Blade number 3. Dof number (1=M_x, 2=M_y, 3=M_z) 4. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	int_rotor_force	Integrated aerodynamic rotor forces. Unit [kN] 1. Coordinate system (3=global, 4=rotor polar) 2. Dof number (1=F_x, 2=F_y, 3=F_z)	No
aero	int_rotor_moment	Integrated aerodynamic rotor moments. Unit [kNm] 1. Coordinate system (3=global, 4=rotor polar) 2. Dof number (1=M_x, 2=M_y, 3=M_z)	No
aero	torque	Integrated aerodynamic forces of all blades to rotor torsion. Unit [kNm]. No parameters. See additional explanations below table.	No
aero	thrust	Integrated aerodynamic forces of all blades to rotor thrust. Unit [kN]. No parameters	No
aero	position	Position of calculation point. Unit [m]. Please be aware that if the blade ref system is used, the orientation is in the blade coo, but the origo is still in the hub center. 1. Coordinates system (1=local aero coo, 2=blade ref. system, 3=global, 4=rotor polar) 2. Blade number 3. Dof number (1=M_x, 2=M_y, 3=M_z) 4. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	power	Integrated aerodynamic forces of all blades to rotor torsion multiplied by the rotor speed. Unit [kW]. No parameters. See additional explanations below table.	No
aero	rotation	Orientation of calculation point. Unit [deg]. 1. Blade number 2. Dof number (1=θ_x, 2=θ_y, 3=θ_z) 3. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used) 4. Coordinate system (1=blade_ref. coo, 2=rotor polar coo.)	No
aero	rotation_e	Orientation of calculation point. Unit [deg]. 1. Blade number	No

Command 1	Command 2	Explanation	Label option
		2. Dof number (1=θ_x, 2=θ_y, 3=θ_z) 3. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used) 4. Coordinate system (1=blade_ref. coo, 2=rotor polar coo.)	
aero	velocity	Velocity of calculation point. Unit [m/s]. 1. Coordinates system (1=local aero coo, 2=blade ref. system, 3=global, 4=rotor polar) 2. Blade number 3. Dof number (1= V_x, 2=V_y, 3=V_z) 4. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	acceleration	Acceleration of calculation point. Unit [m/s2]. 1. Coordinates system (1=local aero coo, 2=blade ref. system, 3=global, 4=rotor polar) 2. Blade number 3. Dof number (1= V_x, 2=V_y, 3=V_z) 4. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	tors_e	Aeroelastic torsional twist minus initial static twist of a blade section. 1. Blade number 2. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	windspeed	Free wind speed seen from the blade. Unit [m/s] 1. Coordinate system (1=local aero coo, 2=blade ref. system, 3=global, 4=rotor polar) 2. Blade number 3. Dof number (1= V_x, 2=V_y, 3=V_z) 4. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used) 5. Tower shadow included (1: with tower shadow, 0: without tower shadow) Note that 5th input argument is optional (default=1)	No
aero	wsp_rotor_avg (New in 12.6.14)	Rotor average free wind speed (excluding tower top motion). Unit [m/s] 1. Coordinate system (1=global; 2=rotor with y perpendicular to the rotor plane, for zero yaw and tilt equivalent to global coordinate system) 3. Dof number (1= V_x, 2=V_y, 3=V_z)	No
aero	spinner_lidar	Sensor emulating a spinner mounted lidar 1. Measurement type (1=single point, 2=volume average) 2. Scan type (1=circular scan, 2=horizontal line (sine sweep), 3=horizontal line (linear sweep), 4=circular 2D scan) 3. Focus length [m] 4. Measurement angle [deg] 5. Scanning velocity [rev/sec] 6. Velocity fraction (2D scan) 7. Beam radius at output lens [m]	No

Command 1	Command 2	Explanation	Label option
		8. Number of points in volume scan 9. Wavelength [m]	
aero	induc	Local induced velocity at calculation point. Unit [m/s] 1. Coordinates system (1=local aero coo, 2=blade ref. system, 3=global, 4=rotor polar) 2. Blade number 3. Dof number (1= V_x, 2=V_y, 3=V_z) 4. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	induc_theodorsen	Local induced velocity from 2D shed vorticity model at calculation point. Only relevant if dynstall_method = 2 or 3. Unit [m/s] 1. Coordinates system (1=local aero coo, 2=blade ref. system, 3=global, 4=rotor polar) 2. Blade number 3. Dof number (1= V_x, 2=V_y, 3=V_z) 4. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	induc_sector_ct	Thrust coefficient at a position on the rotor. Unit [-] 1. Radius [m] 2. Azimuth angle (zero downwards) [deg]	No
aero	induc_sector_cq	Torque coefficient at a position on the rotor. Unit [-] 1. Radius [m] 2. Azimuth angle (zero downwards) [deg]	No
aero	induc_sector_a	Axial induction coefficient at a position on the rotor. Unit [-] 1. Radius [m] 2. Azimuth angle (zero downwards) [deg]	No
aero	induc_sector_am	Tangential induction coefficient at a position on the rotor. Unit [-] 1. Radius [m] 2. Azimuth angle (zero downwards) [deg]	No
aero	induc_a_norm	Axial velocity used in normalization expression of rotor thrust coefficients. The average axial wind velocity excl. induction. Unit [m/s]. No parameters.	No
aero	induc_am_norm	Tangential velocity used in normalization expression of torque coefficient. Average tangential velocity at a given radius. Unit [m/s]. 1. Radius [m]	No
aero	inflow_angle	Angle of attack + rotation angle of profile related to polar coordinates (not pitching). Unit [deg] 1. Blade number 2. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	dcldalfa	Gradient $dCl/d\alpha$. Unit [deg^{-1}] 1. Blade number 2. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No

Command 1	Command 2	Explanation	Label option
aero	dcddalfa	Gradient $dCd/d\alpha$. Unit [deg^{-1}] 1. Blade number 2. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	gamma	Circulation strength at calculation point. Unit [m2/s] 1. Blade number 2. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	lambda	Tip speed ratio, Unit [−]	No
aero	windspeed_boom	Free wind speed seen by a boom mounted on a blade section. Coordinate system used “blade ref. system”. Unit [m/s]. 1. Blade number 2. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used) 3. Boom-length X, measured from half chord point positive towards LE [m] 4. Boom-length Y, measured from half chord point positive towards pressureside [m]	No
aero	actuatordiskload	Actuator disk load provide normalized load export for the Actuator Disk Model. 1. DOF (1=Ft, 2=Fa, 3=Fr) 2. Curved length distance from main_body node 1 [m] (nearest inner calculation point is used)	No
aero	grid_radius_nd	Aerodynamic calculation point non-dim radius r/R 1. Number of radial stations outputted (should normally correspond to number of aerodynamic calculation points on a blade)	No
aero	vawt_induc_x	Induction for a VAWT outputted in tangential polar coordinates 1. disc number 2. azimuth number	No
aero	vawt_induc_y	Induction for a VAWT outputted in radial polar coordinates 1. disc number 2. azimuth number	No
aero	nacelle_lidar	Modified v13.1 (see section 17.9). Model of a single-beam, CW nacelle-mounted lidar. See description Sec. 17.9. Inputs are: 1. Mounting distance from rotor center in global x coordinates [m] 2. Mounting distance from rotor center in global y coordinates [m] 3. Mounting distance from rotor center in global z coordinates [m] 4. Half-cone opening angle of beam [deg] 5. Azimuth angle of beam measured (clockwise as seen from turbine) from vertical up postion [deg] 6. Focus length measured from rotor center (along the beam) [m]	Yes

Command 1	Command 2	Explanation	Label option
		7. Rayleigh length of beam [m] 8. Half-width of integration interval over probe volume, normalized by Rayleigh length [−] 9. Number of integration points [−] 10. Beam identifier number [−] Outputs are (only option supported): 1. Line-of-sight velocity [m/s] 2. Doppler spectrum variance [m2/s2] 3. Global x position of focus point 4. Global y position of focus point 5. Global z position of focus point	
aero	hub_lidar	Implemented v13.1 (see section 17.9). Model of a single-beam, pulsed hub-mounted lidar. See description Sec. 17.9. Inputs are: 1. Half-cone opening angle of beam [deg] 2. Azimuthal angle of beam, measured (anti-clockwise as seen from turbine) from blade1 initial position [deg] 3. Range length of beam, measured along the beam from rotor center [m] 4. Range-gate length (Δ_P) [m] 5. Full width at half-maximum (Δ_L) [m] 6. Half-width of integration interval over probe volume, normalized by Δ_L [−] 7. Number of integration points [−] 8. Beam identifier number [−] Outputs are (only option supported): 1. Global x position of focus point 2. Global y position of focus point 3. Global z position of focus point 4. Lidar line-of-sight velocity [m/s] 5. True (unweighted) line-of-sight velocity [m/s] 6. Free wind component at focus position along global x [m/s] 7. Free wind component at focus position along global y [m/s] 8. Free wind component at focus position along global z [m/s]	Yes
aero	effective_wind_speed	Estimation of rotor effective wind speed as a (weighted) average of longitudinal wind speeds within the rotor area: $v_{eff} = \sqrt[n]{\frac{\int_0^{2\pi}\int_0^R v_u^n(r,\varphi)w(r,\varphi)rdrd\theta}{\int_0^{2\pi}\int_0^R w(r,\varphi)rdrd\theta}}$. Unit [m/s] Inputs are: 1. Number of blades [-] 2. Rotor radius (R) [m] 3. Tip speed ratio at rated wind speed [-] (only used when input 9 is equal to 3) 4. Exclusion of root part [R] (only used when input 9 is equal to 3) 5. Normal measurement distance from rotor plane [m]	No

Command 1	Command 2	Explanation	Label option
		6. Width of turbulence box [m] (use the values from the turbulence box block) 7. Number of integration points along width/height [-] 8. power to weight wind speed with (n) [-] 9. Weighting method: 1: arithmetic mean 2: dCpdr weight w/o losses 3: dCpdr weight with (tip and root) losses 10. Optimum axial induction factor (only used when input 9 is equal to 2 or 3)	
aero	totfrc/totmom	Total aerodynamic force/moment from integration of distributed forces and moment over the blade. Total F_x/M_x, F_y/M_y, F_z/M_z. Unit [kN/kNm]. The sensor can be used for individual blades by specifying the required blade number below; the reference point for the moment is then the location of first aero section. Or the sensor can be the sum over all blades by specifying 'all' below; the reference point for the moment is then the global origin. All forces and moments are output in global coordinates 1. blade number OR 'all' 2. coordinate system in which to output the forces or moments. Beware that the coordinate system for the moments is also specifying the origin.	No

Multi-rotor simulation

For multi-rotor simulation, three commands are used: - Command 1: aero_mr - Command 2: as command 2 from above table - Command 3: name of rotor given in main command block 'aero'. The three commands are followed by the necessary parameters given in the above table.

Additional explanations on aero omega, aero torque and aero power

aero omega Gives the 'aerodynamic' rotor speed, which is an average rotational speed of the blades. In general, it is very similar to the shaft rotor speed, but it may be different especially in case of vibrations in a drivetrain mode. In this case, the blades move edgewise collectively, which means that the 'aero' rotor speed will oscillate around the shafts rotational speed with the frequency of the respective drivetrain mode.

aero torque Aerodynamic torque from integration of the sectional torque over all aerodynamic blade sections. Depending on the aerodynamic (number of aerosections) and structural (number of sections in the c2_def) this torque may differ by up to a few percent from the computed mechanical torque at the shaft. Differences may indicate that a refinement of the aerodynamic and/or structural discretization of the blades is necessary. Further, the aerodynamic torque may be very different from the shaft torque if the rotor speed is not constant. For example in case of an increasing rotor speed, such as due to a gust, a part of the aerodynamic torque will accelerate the rotor and will thus not be felt at the shaft.

aero power This aerodynamic power is computed as the product of the aerodynamic rotor speed and aerodynamic torque above. Therefore it will be different from a mechanical power (shaft moment multiplied by shaft rotational speed) in any of the cases described above:

vibrations of the drivetrain including collective edgewise blade vibrations, insufficient aerodynamic or structural discretization and non-constant rotor speed.

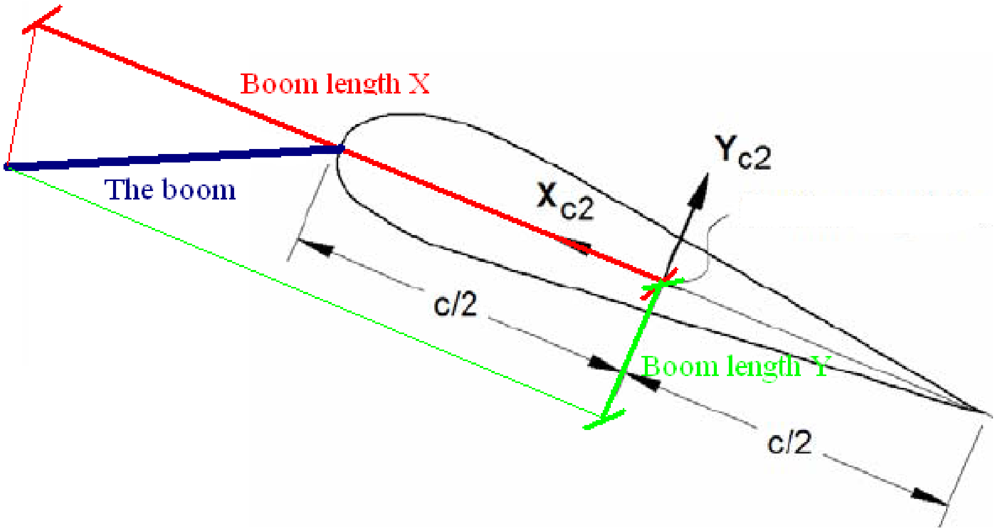


Figure 10: Illustration of the boom coordinates used by the “windspeed_boom” command.

17.13 wind (wind output commands)

Command 1	Command 2	Explanation	Only option	Label option
wind	free_wind	Wind vector V_x, V_y, V_z, (wind as if the turbine didn’t exist). 1. Coordinate system (1=global, 2=non rotating rotor coordinates (x always horizontal, y always out-of-plane)) 2. x-pos (global coo) 3. y-pos (global coo) 4. z-pos (global coo)	Yes	Yes
wind	free_wind_center_pos0	Wind vector V_x, V_y, V_z, (wind as if the turbine didn’t exist). 1. Coordinate system (1=global, 2=non rotating rotor coordinates (x always horizontal, y always out-of-plane)) _center_pos0	Yes	Yes
wind	free_wind_hor	Horizontal wind component velocity [m/s] and direction [deg] defined to output. Dir=0 when wind equals y-dir. 1. Coordinate system (1=global, 2=non rotating rotor coordinates (x always horizontal, y always out-of-plane)) 2. x-pos (global coo) 3. y-pos (global coo) 4. z-pos (global coo)	Yes	Yes
wind	free_wind_-hor_center_pos0	Horizontal wind component velocity [m/s] and direction [deg] defined to output. Dir=0 when wind equals y-dir. 1. Coordinate system (1=global, 2=non rotating rotor coordinates (x always horizontal, y always out-of-plane))	Yes	Yes
wind	free_wind_shadow	As sensor “free_wind”, but with tower shadow included.	Yes	Yes

Command 1	Command 2	Explanation	Only option	Label option
		1. Coordinate system (1=global, 2=non rotating rotor coordinates (x always horizontal, y always out-of-plane)) 2. x-pos (global coo) 3. y-pos (global coo) z-pos (global coo)		

17.14 wind_wake (wind wake output commands)

Command 1	Command 2	Explanation	Only option	Label option
wind_wake	wake_pos	Position of the wake deficit center after the meandering proces to the downstream end position. x,y and z position is written in meteorological coordinates $(x, y, z)_M = (u, v, w)$ with origo in the position defined with center_pos0 in the general wind commands. 1. wake source number	Yes	Yes

17.15 dll (DLL output commands)

Command 1	Command 2	Explanation	Label option
dll	inpvec	Value from DLL input vector is defined to output 1. DLL number 2. array index number	yes
dll	outvec	Value from DLL output vector is defined to output 1. DLL number 2. array index number	yes
dll	hawc_dll	Special output commands for the “hawc_dll” format. With this command the dll name can be used in the output definitions 1. string. Reference name of the dll given in the begin – end hawc_dll input definitions. 2. string. “outvec” or “inpvec” can be used. Same definition as previously written above. 3. Channel number in the in or out going array.	yes
dll	type2_dll	Special output commands for the “type2_dll” format. With this command the dll name can be used in the output definitions 1. string. Reference name of the dll given in the begin – end hawc_dll input definitions. 2. string. “outvec” or “inpvec” can be used. Same definition as previously written above. 3. Channel number in the in or out going array.	yes
dll	sensor_id	Name of sensor_id defined for other output sensor 1. Sensor number if sensor id refers to a vector	

17.16 hydro (hydrodynamic output commands)

Command 1	Command 2	Explanation	Only option	Label option
hydro	water_surface	Water surface level at a given horizontal location is defined to output (global coordinates). Unit [m] 1. x-pos 2. y-pos	No	No
hydro	water_vel_acc	Water velocity V_x, V_y, V_z, and acceleration A_x, A_y, A_z vectors defined to output. Unit [m/s] and [m/s2]. 1. x-pos 2. y-pos 3. z-pos	Yes	No
hydro	water_pressure	Dynamic water pressure from Bernoulli's equation, in a given hydro element calculation point. Unit [MPa]. 1. hydro element number 2. radius (in [m], axial distance from 1st node) 3. coordinate system (1=global, 2=local hydro sec coo)	No	No
hydro	fm	Radial inertia force (FK + hydro mass) F_x, F_y, F_z contribution from Morisons formula in a given calculation point. Unit [kN/m]. Note: added mass is by default computed in the right hand side of the EOM, so the hydro mass term is only accounting for the fluid acceleration term. 1. hydro element number 2. radius (in [m], axial distance from 1st node) 3. coordinate system (1=global, 2=local hydro sec coo)	No	No
hydro	fd	Radial drag force F_x, F_y, F_z contribution from Morisons formula in a given calculation point. Unit [kN/m] 1. hydro element number 2. radius (in [m], axial distance from 1st node) 3. coordinate system (1=global, 2=local hydro sec coo)	No	No
hydro	fb	Buoyancy force (distributed along element) F_x, F_y, F_z contribution in a given calculation point. Unit [kN/m] 1. hydro element number 2. radius (in [m], axial distance from 1st node) 3. coordinate system (1=global, 2=local hydro sec coo)	No	No
hydro	mb	Buoyancy moment (distributed along element) M_x, M_y, M_z contribution in a given calculation point. Unit [kNm/m] 1. hydro element number 2. radius (in [m], axial distance from 1st node) 3. coordinate system (1=global, 2=local hydro sec coo)	No	No

Command 1	Command 2	Explanation	Only option	Label option
hydro	cfb	Concentrated axial buoyancy force F_x, F_y, F_z contribution in a given calculation point. Unit [kN]. Note: in case of auto hydro sections =0, if the specified radius is not a hydro or structural node, the sensor will output the nearest node information. 1. hydro element number 2. radius (in [m], axial distance from 1st node) 3. coordinate system (1=global, 2=local hydro sec coo)	No	No
hydro	cmb	Concentrated buoyancy moment M_x, M_y, M_z contribution in a given calculation point. Unit [kNm]. Note: in case of auto hydro sections =0, if the specified radius is not a hydro or structural node, the sensor will output the nearest node information. 1. hydro element number 2. radius (in [m], axial distance from 1st node) 3. coordinate system (1=global, 2=local hydro sec coo)	No	No
hydro	cfm	Concentrated force from axial hydro mass F_x, F_y, F_z contribution in a given calculation point. Unit [kN]. Added mass is by default computed in the right hand side of the EOM, so the hydro mass term is only accounting for the fluid acceleration term, and computed as $\rho V_{ref} C_{a,axial} water\_acc$, with V_{ref} taken as half volume of sphere defined by the local width (of the specified element radius) as diameter. Note: in case of auto hydro sections =0, if the specified radius is not a hydro or structural node, the sensor will output the nearest node information. 1. hydro element number 2. radius (in [m], axial distance from 1st node) 3. coordinate system (1=global, 2=local hydro sec coo)	No	No
hydro	cfdrag	Concentrated force from axial damping F_x, F_y, F_z contribution in a given calculation point. Unit [kN]. Note: in case of auto hydro sections =0, if the specified radius is not a hydro or structural node, the sensor will output the nearest node information. 1. hydro element number 2. radius (in [m], axial distance from 1st node) 3. coordinate system (1=global, 2=local hydro sec coo)	No	No
hydro	fdyn	Dynamic wave pressure force (distributed) F_x, F_y, F_z contribution in a given calculation point. Unit [kN/m] 1. hydro element number 2. radius (in [m], axial distance from 1st node) 3. coordinate system (1=global, 2=local hydro sec coo)	No	No

Command 1	Command 2	Explanation	Only option	Label option
hydro	cfdyn	Concentrated axial dynamic wave pressure force F_x, F_y, F_z contribution in a given calculation point. Unit [kN]. Note: in case of auto hydro sections =0, if the specified radius is not a hydro or structural node, the sensor will output the nearest node information. 1. hydro element number 2. radius (in [m], axial distance from 1st node) 3. coordinate system (1=global, 2=local hydro sec coo)	No	No
hydro	secfrc	Total hydro distributed force F_x, F_y, F_z contribution in a given calculation point. Unit [kN/m] 1. hydro element number 2. radius (in [m], axial distance from 1st node) 3. coordinate system (1=global, 2=local hydro sec coo)	No	No
hydro	secmom	Total hydro distributed moment M_x, M_y, M_z contribution in a given calculation point. Unit [kNm/m] 1. hydro element number 2. radius (in [m], axial distance from 1st node) 3. coordinate system (1=global, 2=local hydro sec coo)	No	No
hydro	cfrc	Total hydro axial concentrated force F_x, F_y, F_z contribution in a given calculation point. Unit [kN]. Note: in case of auto hydro sections =0, if the specified radius is not a hydro or structural node, the sensor will output the nearest node information. 1. hydro element number 2. radius (in [m], axial distance from 1st node) 3. coordinate system (1=global, 2=local hydro sec coo)	No	No
hydro	totfrc/totmom	Total hydro force/moment from integration of distributed forces and moment over the hydro element. Total F_x/M_x, F_y/M_y, F_z/M_z. Unit [kN/kNm]. The sensor can be used for individual hydro elements by specifying the required hydro element number below; the reference point for the moment is then the location of first hydro section. Or the sensor can be the sum over all hydro elements by specifying 'all' below; the reference point for the moment is then the global origin. All forces and moments are output in global coordinates 1. hydro element number OR 'all' 2. coordinate system in which to output the forces or moments. Beware that the coordinate system for the moments is also specifying the origin.	No	No

17.17 External forces

Command 1	Command 2	Explanation	Label option
force		1. Name of the force DLL.	No

17.18 general (general output commands)

Command 1	Command 2	Explanation	Label option
general	constant	A constant value is send to output 1. constant value	Yes
general	step	A step function is created. This function changes from f_0 to f_1 at time t_0. 1. t_0 [sec] 2. f_0 3. f_1	Yes
general	step2	A step function is created. This function changes from f_0 to f_1 between time t_0 and t_1 using linear interpolation. 1. t_0 [sec] 2. t_1 [sec] 3. f_0 4. f_1	Yes
general	step3	A step function is created. This function changes from f_0 to f_1 between time t_0 and t_1 using a continous sinus2 interpolation function. 1. t_0 [sec] 2. t_1 [sec] 3. f_0 4. f_1	Yes
general	time	The time is send to output. No parameters	Yes
general	deltat	The time increment is send to output. No parameters	Yes
general	harmonic	A harmonic function is send to output $F(t) = A\sin(2\pi f_0 t) + k$ 1. A 2. f_0 3. k	Yes
general	harmonic2	A harmonic function is send to output $$F(t) = \begin{cases} 0 & t < t_0 \\ A\sin(2\pi f_0(t - t_0)) + k & t_0 \le t \le t_1 \\ 0 & t > t_1 \end{cases}$$ 1. A 2. f_0 3. k 4. t_0 5. t_1	Yes
general	stairs	A series of steps resulting in a staircase signal is created. 1. t_0 time for first step change [s] 2. f_0 start value of function 3. Step size	Yes

Command 1	Command 2	Explanation	Label option
		4. Step duration [s] 5. Number of steps	
general	status	A status flag (mainly for controller purpose) is written. A first time step and first iteration the output value is 0. During the rest of the simulation the value is 1 until last time step where the value is -1.	Yes
general	random	A randon (uniform distribution) is written 1. lower limit 2. upper limit 3. seed number	Yes
general	impulse	A step function which return to zero after a certain duration 1. t_0 time for impulse start [s] 2. Impulse duration [s] 3. f_0 impulse level	Yes
general	sensor_id	Sensor name. 1. Sensor name 2. Sensor number if sensor name refers to a vector	No
general	variable	Sensor, which can be modified via API in library version of HAWC2. 1. Sensor index (custom index, 1-100, use to refer to the sensor) 2. Initial sensor value Name, unit and description can be specified as described in Sec. 17.3	No

18 Output_at_time (output at a given time)

This command is especially usefull if a snapshot of loads or other properties are required at a specific time. This is mostly used for writing calculated aerodynamic properties as function of blade location. The command block can be repeated as many times as needed (e.g. if outputs at more than one time is needed)

The command must be written with the following syntax

```
output_at_time keyword time
```

where *keyword* is the name of an output subcommand. Currently only the subcommand *aero* is supported. The last command word time is the time in seconds from simulation start to which the output are written.

18.1 aero (aerodynamic output commands)

The first line in the output_at block must be the information regarding which file the outputs are written (the filename command listed in the table below)

Command 1	Explanation	Label option
filename	Filename incl. relative path to output file	No

Command 1	Explanation	Label option
	(example ./output/output_at.dat). 1. filename	
alfa	Angle of attack [deg]. 1. Blade number	No
alfadot	Pitch rate term (z-axis rotation) in local aerodynamic plane, as used for non-circulatory contributions. Unit [rad/s]. 1. Blade number	No
vrel	Relative velocity [m/s] 1. Blade number	No
cl	Lift coefficient [-] 1. Blade number	No
cd	Drag coefficient [-] 1. Blade number	No
cm	Moment coefficient [-] 1. Blade number	No
lift	Lift force L [N/m] 1. Blade number	No
drag	Drag force D [N/m] 1. Blade number	No
moment	Moment force M [Nm/m] 1. Blade number	No
secforce	Aerodynamic forces [kN/m] 1. Blade number 2. DOF number (1=x,2=y,3=z) 3. Coordinate system (1=aero, 2=blade, 3=global, 4=rotor polar)	No
secmoment	Aerodynamic moments [kNm/m] 1. Blade number 2. DOF number (1=x,2=y,3=z) 3. Coordinate system (1=aero, 2=blade, 3=global, 4=rotor polar)	No
int_force	Aerodynamic forces integrated from tip to given radius [kN] 1. Blade number 2. DOF number (1=x,2=y,3=z) 3. Coordinate system (1=aero, 2=blade, 3=global, 4=rotor polar)	No
int_moment	Aerodynamic moment integrated from tip to given radius [kNm] 1. Blade number 2. DOF number (1=x,2=y,3=z) 3. Coordinate system (1=aero, 2=blade, 3=global, 4=rotor polar)	No
inipos	Initial position of sections in blade coo [m] 1. Blade number 2. DOF number (1=x,2=y,3=z)	No
position	Actual position of section [m] 1. Blade number 2. DOF number (1=x,2=y,3=z) 3. Coordinate system (1=aero, 2=blade, 3=global, 4=rotor polar)	No
velocity	Actual velocity of section [m/s] 1. Blade number 2. DOF number (1=x,2=y,3=z) 3. Coordinate system (1=aero, 2=blade, 3=global, 4=rotor polar)	No
acceleration	Actual acceleration of section [m/s] 1. Blade number 2. DOF number (1=x,2=y,3=z) 3. Coordinate system (1=aero, 2=blade, 3=global, 4=rotor polar)	No

Command 1	Explanation	Label option
ct_local	Local thrust coefficient [-]. Calculated based on the expression $C_t = \frac{F_{axial}\, B}{{}^1/_2 \rho 2\pi\, r\, V_{\text{inf}}^2}$ 1. Blade number	No
cq_local	Local tangential force coefficient [-]. Calculated based on the expression $C_q = \frac{F_{\tan}\, B}{{}^1/_2 \rho 2\pi\, r\, V_{\text{inf}}^2}$ 1. Blade number	No
chord	Chord length [m] 1. Blade number	No
induc	Induced velocity [m/s] 1. Blade number 2. DOF number (1=x,2=y,3=z) 3. Coordinate system (1=aero, 2=blade, 3=global, 4=rotor polar)	No
windspeed	Free windspeed (without induction) [m/s] 1. Blade number 2. DOF number (1=x,2=y,3=z) 3. Coordinate system (1=aero, 2=blade, 3=global, 4=rotor polar) 4. Include tower shadow (1: with tower shadow, 0: without tower shadow) Note that the 4th input argument is optional (default =1)	No
inflow_angle	Angle of attack + rotation angle of profile related to polar coordinates (not pitching). Unit [deg] 1. Blade number	No
dcldalfa	Gradient $dCl/d\alpha$. Unit [deg^{-1}] 1. Blade number	No
dcddalfa	Gradient $dCd/d\alpha$. Unit [deg^{-1}] 1. Blade number	No
tiploss_f	The local tiploss factor (product of Prandtl and custom tiploss factor) 1. Blade number	No

An example of an output_at_time command block could be:

```
begin output_at_time aero 100;
  filename ./output_at_time ;
  alfa 1;
end output_at_time;
```

19 Input file encryption

19.1 DLL format

As of version 13.2, the DLL format is deprecated, and it will be removed in the next release of HAWC2. Users are advised to use the encrypted binary format instead. If you need any help converting files, or getting started using the binary encrypted format, feel free to contact the HAWC2 support.

From version 11.6 it is possible to attach a DLL from where the blade data can be extracted. In doing so, the user is not able to inspect the blade input data from a readable text file. This approach requires a Fortran Intel compiler setup (when using a DTU provided template) from the data owner in order to compile the blade data into a DLL. The user refers to the external blade data in DLL format in the `new_htc_structure` and `aero` sections using the `external_bladedata_dll` command (as described earlier in this manual in the relevant sections).

19.2 Encrypted binary format

Starting from version 12.8, a new method to hide confidential input data is offered. This approach allows the data owner to encrypt normal HAWC2 input data files into files that only HAWC2 is able to read. The encryption is performed by an executable, which is provided by the HAWC2 support, hawc2@windenergy.dtu.dk, upon request. Note, the executable is only needed to generate the encrypted input data, i.e. no additional tools are needed by the end user to use the encrypted data files.

19.2.1 How to encrypt data files

Data files are encrypted from command line as follows:

```
> EncryptDataFile.exe mydatafile.dat
```

This will generate the encrypted file `mydatafile.dat.enc`

19.2.2 Using encrypted data files

To use the data file with HAWC2, simply replace the data file name in the htc file.

HAWC2 will recognize and decrypt `*.enc` files for the following types of files:

- Timoschenko input (`new_htc_structure/main_body/timoschenko_input/filename`)
- Aero dynamic layout (`aero/ae_filename`)
- Profile coefficients (`aero/pc_filename`)
- HTC sub files (`continue_in_file`). NOTE: No output options are disabled. The user may be able to output your confidential data via output sensors or other output options

19.2.3 Disabled output

When the aerodynamic layout or profile coefficients are encrypted, the following output options are unavailable:

- output:

  - cl, cd, cm
  - lift, drag, moment
  - induc
  - induc_sector_ct, induc_sector_cq
  - induc_sector_a, induc_sector_am
  - induc_a_norm
  - induc_am_norm
  - dcldalfa, dcddalfa
  - secforce, secmoment
  - int_force, int_moment
  - vawt_induc_x, vawt_induc_y
  - grid_all_ct, grid_all_induc_u
- Output_at_time:
  - cl, cd, cm
  - lift, drag, moment
  - ct_local, cq_local
  - chord, twist
  - dcldalfa, dcddalfa
  - induc
  - secforce, secmoment
  - int_force, int_moment
  - vawt_qn, vawt_qt
  - vawt_induc_x, vawt_induc_y
- output_profile_coef_filename

When the Timoschenko input file is encrypted, the following output options are unavailable:

- new_htc_structure
  - beam_output_file_name
  - body_output_file_name
  - struct_inertia_output_file_name
  - body_matrix_output
  - element_matrix_output

20 Examples and Reference Models

A selection of specific examples is maintained at the following git repository:

`https://gitlab.windenergy.dtu.dk/HAWC2Public/examples`.

A collection of public reference HAWC2 models is available at:

`https://gitlab.windenergy.dtu.dk/hawc-reference-models/`.

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A Example of main input file

```
begin Simulation;
  time_stop    100;
  solvertype   2 ;    (sparse newmark)
  on_no_convergence continue ;
  logfile ./log/oc3_monopile_phase_1.log ;
  animation ./animation/oc3_monopile_phase_1.dat;
;
  begin newmark;
    deltat    0.02;
  end newmark;
end simulation;
;
begin new_htc_structure;
  ; Optional - Calculated beam properties of the bodies are written to file:
  beam_output_file_name  ./log/oc3_monopile_phase_1_beam.dat;
  ; Optional - Body initial position and orientation are written to file:
  body_output_file_name  ./log/oc3_monopile_phase_1_body.dat;
;  body_eigenanalysis_file_name ./eigenfrq/oc3_monopile_phase_1_body_eigen.dat;
;  structure_eigenanalysis_file_name ./eigenfrq/oc3_monopile_phase_1_strc_eigen.dat ;
;-------------------------------------------------------------------------------------
;
  begin main_body;          monopile 30m
    name        monopile ;
    type        timoschenko ;
    nbodies     1 ;
    node_distribution     c2_def ;
    damping   4.5E-02 4.5E-02 8.0E-01 1.2E-03 1.2E-03 4.5E-04 ;
    begin timoschenko_input;
      filename ./data/Monopile.txt ;
      set 1 1 ;                set subset   1=flexible,2=stiff
    end timoschenko_input;
    begin c2_def;              Definition of centerline (main_body coordinates)
      nsec 7;
      sec 1 0.0 0.0 0.0    0.0 ;  x,y,z,twist      Mudline
      sec 2 0.0 0.0 -0.1    0.0 ;  x,y,z,twist
      sec 3 0.0 0.0 -10.0    0.0 ;  x,y,z,twist    50% between mudline and MSL
      sec 4 0.0 0.0 -15.0    0.0 ;  x,y,z,twist
      sec 5 0.0 0.0 -20.0    0.0 ;  x,y,z,twist    MWL
      sec 6 0.0 0.0 -25.0  0.0 ;
      sec 7 0.0 0.0 -30.0 0.0 ;                           Monopile flange
    end c2_def ;
  end main_body;
;
  begin main_body;         tower 80m
    name        tower ;
    type        timoschenko ;
    nbodies     1 ;
    node_distribution     c2_def ;
     damping_posdef   6.456E-4 6.45E-4 1.25E-3 1.4E-3 1.4E-3 1.25E-3 ;
     ;damping_posdef Mx My Mz Kx Ky Kz , M´s raises overall level, K´s raises high freguency level
     ;
    begin timoschenko_input;
      filename ./data/NREL_5MW_st.txt ;
      set 1 1 ;
    end timoschenko_input;
    begin c2_def;              Definition of centerline (main_body coordinates)
      nsec 8;
      sec 1 0.0 0.0 0.0    0.0 ;  x,y,z,twist
      sec 2 0.0 0.0 -10.0  0.0 ;
      sec 3 0.0 0.0 -20.0  0.0 ;
      sec 4 0.0 0.0 -30.0  0.0 ;
      sec 5 0.0 0.0 -40.0  0.0 ;
```

```
      sec 6 0.0 0.0 -50.0  0.0 ;
      sec 7 0.0 0.0 -60.0 0.0 ;
      sec 8 0.0 0.0 -77.6 0.0 ;
     end c2_def ;
    end main_body;
;
  begin main_body;
    name        towertop ;
    type        timoschenko ;
    nbodies     1 ;
    node_distribution     c2_def ;
;    damping_posdef   9.025E-06 9.025E-06 8.0E-05 8.3E-06 8.3E-06 8.5E-05 ;
    damping  2.50E-04  1.40E-04  2.00E-03  3.00E-05  3.00E-05  2.00E-04  ;
    ;
    ;Nacelle mass and inertia:
    concentrated_mass 2 0.0  1.9 0.21256 2.4E5 1741490.0  1.7E5 1741490.0 ;
        begin timoschenko_input;
      filename ./data/NREL_5MW_st.txt ;
      set 2 1 ;
    end timoschenko_input;
    begin c2_def;              Definition of centerline (main_body coordinates)
      nsec 2;
      sec 1 0.0 0.0 0.0       0.0 ; x,y,z,twist
      sec 2 0.0 0.0 -1.96256  0.0 ;
    end c2_def ;
  end main_body;
;
  begin main_body;
    name        shaft ;
    type        timoschenko ;
    nbodies     1 ;
    node_distribution     c2_def ;
;   damping_posdef  7.00E-3  7.00E-03  7.00E-02  3.48E-04  3.48E-04  1.156E-03 ;
   damping_posdef  7.00E-3  7.00E-03  7.00E-02  6.5E-04  6.5E-04  1.84E-02 ;
          concentrated_mass 1 0.0 0.0 0.0 0.0 0.0 0.0 5025497.444 ;generator equivalent slow shaft
    concentrated_mass 5 0.0 0.0 0.0 56780 0.0 0.0 115926 ; hub mass and inertia;
        begin timoschenko_input;
      filename ./data/NREL_5MW_st.txt ;
      set 3 1 ;
    end timoschenko_input;
    begin c2_def;              Definition of centerline (main_body coordinates)
      nsec 5;
      sec 1 0.0 0.0 0.0     0.0 ; Tower top x,y,z,twist
      sec 2 0.0 0.0 1.0     0.0 ;
      sec 3 0.0 0.0 2.0     0.0 ;
      sec 4 0.0 0.0 3.1071  0.0 ; Main bearing
      sec 5 0.0 0.0 5.0191  0.0 ; Rotor centre
    end c2_def ;
  end main_body;
;
  begin main_body;
    name        hub1 ;
    type        timoschenko ;
    nbodies     1 ;
    node_distribution     c2_def ;
    damping_posdef  2.00E-05  2.00E-05  2.00E-04  3.00E-06  3.00E-06  2.00E-05;
        begin timoschenko_input;
      filename ./data/NREL_5MW_st.txt ;
      set 4 1 ;
    end timoschenko_input;
    begin c2_def;              Definition of centerline (main_body coordinates)
      nsec 2;
      sec 1 0.0 0.0 0.0     0.0 ; x,y,z,twist
      sec 2 0.0 0.0 1.5   0.0 ;
    end c2_def ;
```

```
  end main_body;
;
  begin main_body;
    name           hub2 ;
    copy_main_body hub1;
  end main_body;
;
  begin main_body;
    name           hub3 ;
    copy_main_body hub1 ;
  end main_body;
;
  begin main_body;
    name        blade1 ;
    type        timoschenko ;
    nbodies     9 ;
    node_distribution    c2_def;
;   damping   3.5e-2 5.5e-4 5.0e-4 3.0e-4 0.5e-3 5.5e-3  ;
    damping_posdef   1.16e-4 5.75e-5 6.1e-6 6.5e-4 5.1e-4 6.4e-4 ;
   begin timoschenko_input ;
      filename ./data/NREL_5MW_st.txt ;
      set 5 1 ;                set subset
    end timoschenko_input;
    begin c2_def;              Definition of centerline (main_body coordinates)
      nsec 19 ;
        sec 1         0.0000        0.0000        0.000        0.000                ;        x.y.z. twist
        sec 2       -0.0041        0.0010        1.367        -13.308                ;
        sec 3       -0.1058        0.0250        4.100        -13.308                ;
        sec 4       -0.2502        0.0592        6.833        -13.308                ;
        sec 5       -0.4594        0.1087        10.250        -13.308                ;
        sec 6       -0.5699        0.1157        14.350        -11.480                ;
        sec 7       -0.5485        0.0983        18.450        -10.162                ;
        sec 8       -0.5246        0.0832        22.550        -9.011                ;
        sec 9       -0.4962        0.0679        26.650        -7.795                ;
        sec 10       -0.4654        0.0534        30.750        -6.544                ;        50% blade radius
        sec 11       -0.4358        0.0409        34.850        -5.361                ;
        sec 12       -0.4059        0.0297        38.950        -4.188                ;
        sec 13       -0.3757        0.0205        43.050        -3.125                ;
        sec 14       -0.3452        0.0140        47.150        -2.319                ;
        sec 15       -0.3146        0.0084        51.250        -1.526                ;
        sec 16       -0.2891        0.0044        54.667        -0.863                ;
        sec 17       -0.2607        0.0017        57.400        -0.370                ;
        sec 18       -0.1774        0.0003        60.133        -0.106                ;
        sec 19       -0.1201        0.0000        61.500        -0.000                ;
   end c2_def ;
  end main_body;
;
  begin main_body;
    name           blade2 ;
    copy_main_body blade1;
  end main_body;
;
  begin main_body;
    name           blade3 ;
    copy_main_body blade1 ;
  end main_body;
;-------------------------------------------------------------------------------------
;
  begin orientation;
    begin base;
      body   monopile;
      inipos        0.0 0.0 20.0 ;         initial position of node 1
      body_eulerang 0.0 0.0 0.0;
```

```
    end base;
;
    begin relative;
      body1  monopile last;         indtil videre antages der internt i programmet at der
    ;                               altid kobles mellen sidste knude body1 og første
    ;                               knude body 2
      body2  tower 1;
      body2_eulerang 0.0 0.0 0.0;
    end relative;
;
    begin relative;
      body1  tower last;
      body2  towertop 1;
      body2_eulerang 0.0 0.0 0.0;
    end relative;
;
    begin relative;
      body1  towertop last;
      body2  shaft 1;
      body2_eulerang 90.0 0.0 0.0;
      body2_eulerang 5.0 0.0 0.0;    5 deg tilt angle
      ;body initial rotation velocity x.y.z.angle velocity[rad/s]  (body 2 coordinates):
      body2_ini_rotvec_d1 0.0 0.0 -1.0 0.5 ;
    end relative;
;
    begin relative;
      body1  shaft last;
      body2  hub1 1;
      body2_eulerang -90.0 0.0 0.0;
      body2_eulerang 0.0 180.0 0.0;
      body2_eulerang 2.5 0.0 0.0;      2.5deg cone angle
    end relative;
;
    begin relative;
      body1  shaft last;
      body2  hub2 1;
      body2_eulerang -90.0 0.0 0.0;
      body2_eulerang 0.0 60.0 0.0;
      body2_eulerang 2.5 0.0 0.0;      2.5deg cone angle
    end relative;
;
    begin relative;
      body1  shaft last;
      body2  hub3 1;
      body2_eulerang -90.0 0.0 0.0;
      body2_eulerang 0.0 -60.0 0.0;
      body2_eulerang 2.5 0.0 0.0;      2.5deg cone angle
    end relative;
;
    begin relative;
      body1  hub1 last;
      body2  blade1 1;
      body2_eulerang 0.0 0.0 0;
    end relative;
;
    begin relative;
      body1  hub2 last;
      body2  blade2 1;
      body2_eulerang 0.0 0.0 0.0;
    end relative;
;
    begin relative;
      body1  hub3 last;
      body2  blade3 1;
      body2_eulerang 0.0 0.0 0.0;
```

```
    end relative;
;
         end orientation;
;-------------------------------------------------------------------------
begin constraint;
;
    begin fix0;  fixed to ground in translation and rotation of node 1
      body monopile;
    end fix0;
;
    begin fix1;  fixed relative to other body in translation and rotation
      body1 monopile last;
      body2 tower 1;
    end fix1;
;
    begin fix1;
      body1 tower last ;
      body2 towertop 1;
    end fix1;
;
    begin bearing1;                       free bearing
     name  shaft_rot;
      body1 towertop last;
      body2 shaft 1;
      bearing_vector 2 0.0 0.0 -1.0;        x=coo (0=global.1=body1.2=body2) vector in body2
      ;                                     coordinates where the free rotation is present
   end bearing1;
;
     begin fix1;
       body1 shaft last ;
       body2 hub1 1;
     end fix1;
;
     begin fix1;
       body1 shaft last ;
       body2 hub2 1;
     end fix1;
;
     begin fix1;
       body1 shaft last ;
       body2 hub3 1;
    end fix1;
;
    begin bearing2;
      name pitch1;
      body1 hub1 last;
     body2 blade1 1;
                        bearing_vector 2 0.0 0.0 -1.0;
   end bearing2;
;
    begin bearing2;
      name pitch2;
      body1 hub2 last;
      body2 blade2 1;
                        bearing_vector 2 0.0 0.0 -1.0;
    end bearing2;
;
    begin bearing2;
      name pitch3;
      body1 hub3 last;
      body2 blade3 1;
                        bearing_vector 2 0.0 0.0 -1.0;
    end bearing2;
end constraint;
;
```

```
end new_htc_structure;
;----------------------------------------------------------------------
begin wind ;
  density                 1.25;
  wsp                     8  ;
  horizontal_input        1;
  windfield_rotations     0.0  0.0  0.0 ;    yaw, tilt, rotation
  center_pos0             0.0 0.0 -90.00;      hub_height
  shear_format            3 0.12;
  turb_format             1     ;  0=none, 1=mann,2=flex
  tower_shadow_method     1;
  tint                    0.06 ;
  scale_time_start        200;
  wind_ramp_factor   0.0 200 0.5 1.0 ;
  ;------------------------------------------------------------------
  begin tower_shadow_potential;
    tower_offset 0.0;
    nsec  2;
    radius      0.0   2.10;
    radius     -68.10 1.15;
  end tower_shadow_potential;
  ;------------------------------------------------------------------
  ; This next part is only to be include in case of wake effects being studied
  begin wakes;
    nsource 35;
    source_pos        2548        -2900        -90        ;
    source_pos        2123        -2417        -90        ;
    source_pos        1706        -1942        -90        ;
    source_pos        1281        -1458        -90        ;
    source_pos        857        975        -90        ;        WT5
    source_pos        432        491        -90        ;        WT6
    source_pos        -425        -484        -90        ;        WT8
    source_pos        -850        -968        -90        ;        WT9
    source_pos        -1267        1458        -90        ;
    source_pos        -1700        1935        -90        ;
    source_pos        -2125        2419        -90        ;
    source_pos        3556        -2533        -90        ;
    source_pos        3131        -2049        -90        ;
    source_pos        2706        -1565        -90        ;
    source_pos        2281        1081        -90        ;        WT16
    source_pos        1602        308        -90        ;        WT17
    source_pos        1176        -176        -90        ;        WT18
    source_pos        751        -660        -90        ;        WT19
    source_pos        326        -1144        -90        ;        WT20
    source_pos        -99        -1627        -90        ;        WT21
    source_pos        3915        -1427        -90        ;
    source_pos        3486        -943        -90        ;
    source_pos        3062        -455        -90        ;
    source_pos        2405        -292        -90        ;        WT25
    source_pos        1927        -836        -90        ;        WT26
    source_pos        1502        -1319        -90        ;        WT27
    source_pos        1077        -1803        -90        ;        WT28
    source_pos        652        -2287        -90        ;        WT29
    source_pos        4235        -283        -90        ;
    source_pos        3813        205        -90        ;
    source_pos        3163        944        -90        ;
    source_pos        2679        1495        -90        ;
    source_pos        2254        1979        -90        ;
    source_pos        1829        2463        -90        ;
    source_pos        1404        2947        -90        ;
    op_data      1.4252392 2 ; 1.8 -23.1 ;1.87 0.0 rad/sec, pitch [grader] opstrøms;
    ble_parameters 0.10 0.008 0;
    begin mann_meanderturb ;
      create_turb_parameters 33.6 1 3.7 508 0.0 ;      L, alfaeps,gamma,seed, highfrq compensation
      filename_v    ./free_sector_monopile/wake-meander/wake_meand_turb_wsp8_s508_t1800v.bin ;
```

```
      filename_w    ./free_sector_monopile/wake-meander/wake_meand_turb_wsp8_s508_t1800w.bin ;
      box_dim_u   16384 1.7578125 ;
      box_dim_v     32 90 ;
      box_dim_w     32 90 ;
    end mann_meanderturb;
;
    begin mann_microturb ;
      create_turb_parameters 8.0 1.0 1.0 508 1.0 ;      L, alfaeps,gamma,seed, highfrq compensation
      filename_u    ./free_sector_monopile/wake-micro/wake_turb_wsp8_s508_t1800u.bin ;
      filename_v    ./free_sector_monopile/wake-micro/wake_turb_wsp8_s508_t1800v.bin ;
      filename_w    ./free_sector_monopile/wake-micro/wake_turb_wsp8_s508_t1800w.bin ;
      box_dim_u   128 1.0 ;
      box_dim_v     128 1.0 ;
      box_dim_w     128 1.0 ;
    end mann_microturb;
  end wakes;
  ;-----------------------------------------------------------------
  begin mann;
    create_turb_parameters 33.6 1 3.7 508 1.0 ;      L, alfaeps,gamma,seed, highfrq compensation
    filename_u    ./free_sector_monopile/turb/turb_wsp8_s508_t1800u.bin ;
    filename_v    ./free_sector_monopile/turb/turb_wsp8_s508_t1800v.bin ;
    filename_w    ./free_sector_monopile/turb/turb_wsp8_s508_t1800w.bin ;
    box_dim_u    16384 1.7578125 ;
    box_dim_v    32 3.75;
    box_dim_w    32 3.75;
  end mann;
end wind;;
begin aero ;
  nblades  3;
  hub_vec shaft -3 ;         rotor rotation vector (normally shaft component directed from
  ;                          pressure to suction side)
  link 1 mbdy_c2_def blade1;
  link 2 mbdy_c2_def blade2;
  link 3 mbdy_c2_def blade3;
  ae_filename        ./data/NREL_5MW_ae.txt;
  pc_filename        ./data/NREL_5MW_pc.txt;
  induction_method   1 ;     0=none, 1=normal
  aerocalc_method    1 ;     0=ingen aerodynamic, 1=med aerodynamic
  aerosections       30 ;
  ae_sets            1 1 1;
  tiploss_method     1 ;     0=none, 1=prandtl
  dynstall_method    2 ;     0=none, 1=stig øye method,2=mhh method
end aero ;
;
;--------------------------------------------------------------------------------------------------
 begin hydro;
   begin water_properties;
     rho 1027 ; kg/m^3
     gravity 9.81 ; m/s^2
     mwl 0.0 ;
     mudlevel 20.0 ;
     water_kinematics_dll ./wkin_dll.dll   ./htc_hydro/reg_airy_h6_t10.inp ;
 end water_properties;
;
   begin hydro_element;
     body_name monopile ;
     hydrosections uniform 50 ; distribution of hydro calculation points from sec 1 to nsec
     nsec 2;
     sec 0.0 1.0 1.0 28.27 28.27 6.0 ;  nr z Cm Cd V Vr width
     sec 30.0 1.0 1.0 28.27 28.27 6.0 ;  nr z Cm Cd V Vr width
   end hydro_element;
 end hydro;
;
;--------------------------------------------------------------------------------------------
begin dll;
```

```
  begin hawc_dll;
    filename  ./control/bladed2hawc.dll ;
    dll_subroutine regulation ;
    arraysizes  15 15 ;
    deltat  0.02;
    begin output;
      general time ;
      constraint bearing2 pitch1 1;  angle and angle velocity written to dll
      constraint bearing2 pitch2 1;  angle and angle velocity written to dll
      constraint bearing2 pitch3 1;  angle and angle velocity written to dll
      constraint bearing2 shaft_rot 1; angle and angle velocity written to dll  (slow speed shaft)
      wind free_wind 1 0.0 0.0 -90.55; local wind at fixed position: coo
      general constant 97.0 ;                  generator exchange ratio
    end output;
;
    begin actions;
      body moment_int shaft 1 3 towertop 2 ;
    end actions;
  end hawc_dll;
;
  begin hawc_dll;
    filename  ./control/pitchservo_pos.dll ;
    dll_subroutine servo ;
    arraysizes  15 15 ;
    deltat    0.02 ;
    begin output;
      general time ;                                                                 1
      dll inpvec 1 2;                                                                2
      dll inpvec 1 3;                                                                3
      dll inpvec 1 4;                                                                4
      constraint bearing2 pitch1 1;  angle and angle velocity written to dll        5,6
      constraint bearing2 pitch2 1;  angle and angle velocity written to dll        7,8
      constraint bearing2 pitch3 1;  angle and angle velocity written to dll        9,10
    end output;
;
    begin actions;
      body bearing_angle pitch1;
      body bearing_angle pitch2;
      body bearing_angle pitch3;
    end actions;
  end hawc_dll;
;
   begin hawc_dll;
    filename  ./control/damper.dll ;
    dll_subroutine damp ;
    arraysizes  15 15 ;
    begin output;
      general time ;                                                                 1
      general constant 5.0;
      general constant 10.0;
      general constant -1.0E1 ;
      mbdy state vel towertop 1 1.0 tower;
   end output;
;
    begin actions;
       mbdy force_ext towertop 2 1 towertop;
            mbdy force_ext towertop 2 2 towertop;
    end actions;
  end hawc_dll;
end dll;
;
;----------------------------------------------------------------------------------
;
begin output;
  filename ./res/oc3_monopile_phase_1 ;
```

```
;  time 390.0 450.0 ;
  buffer 1 ;
  general time;
  data_format  hawc_binary;
;
  constraint bearing1 shaft_rot 2; angle and angle velocity
  constraint bearing2 pitch1 5;    angle and angle velocity
  constraint bearing2 pitch2 5;    angle and angle velocity
  constraint bearing2 pitch3 5;    angle and angle velocity
  aero omega ;
  aero torque;
  aero power;
  aero thrust;
  wind free_wind 1 0.0 0.0 -90.0; local wind at fixed position: coo
  hydro water_surface 0.0 0.0 ;        x,y   gl. pos
  mbdy momentvec towertop 1 2 towertop # yaw bearing ;
  mbdy forcevec  towertop 1 2 towertop # yaw bering ;
  mbdy momentvec shaft 4 1  shaft # main bearing ;
  mbdy momentvec blade1 3  1 blade1 # blade 1 root ;
  mbdy momentvec blade1 10 1 local # blade 1 50% local e coo ;
  mbdy momentvec hub1 1  2 hub1 # blade 1 root ;
  mbdy momentvec hub2 1  2 hub2 # blade 2 root ;
  mbdy momentvec hub3 1  2 hub3 # blade 3 root ;
  mbdy state pos towertop   1 1.0 global # tower top flange position ;
  mbdy state pos tower   1 0.0 global # tower MSL position ;
  mbdy state pos blade1  18 1.0 blade1 # blade 1 tip pos ;
  mbdy state pos blade2  18 1.0 blade2 # blade 2 tip pos ;
  mbdy state pos blade3  18 1.0 blade3 # blade 3 tip pos ;
  mbdy state pos blade1  18 1.0 global # blade 1 tip pos ;
  aero windspeed 3 1 1 63.0;   wind seen from the blade:
  ;                            coo(1=local ae,2=blade,3=global,4=rotor polar),
  aero windspeed 3 1 2 63.0;
  aero windspeed 3 1 3 63.0;
  aero alfa 1 45.0;
  aero alfa 2 45.0;
  aero alfa 3 45.0;
  mbdy momentvec towertop 1 1 tower # tower top -1: below top mass ;
  mbdy forcevec  towertop 1 1 tower # tower top -1: below top mass ;
  mbdy momentvec tower  1 1 tower # tower MSL ;
  mbdy forcevec  tower  1 1 tower # tower MSL ;

; mbdy statevec_new mbdyname center coo elastic/absolute r sign xy_vector:
  mbdy statevec_new blade1 c2def   blade1 elastic  88.0 1.d0 0.0 0.0
  mbdy statevec_new blade1 default blade1 elastic  88.0 1.d0 0.0 0.0 ;
  mbdy statevec_new blade1 c2def   blade1 absolute 88.0 1.d0 0.0 0.0 ;
  mbdy statevec_new blade1 default blade1 absolute 88.0 1.d0 0.0 0.0 ;
  mbdy statevec_new blade1 default global absolute 88.0 1.d0 0.0 0.0 ;

; mbdy forcemomentvec_interp mbdy_name center coo_mbdy curved_distance_from_orig sign
  mbdy forcemomentvec_interp blade1 default blade1 5 1.0 # blade1 R= 5 ;
  mbdy forcemomentvec_interp blade1 default blade1 55 1.0 # blade1 R=55  ;
  mbdy forcemomentvec_interp blade1 c2def local_aero 35 1.0 # blade1 R=35  ;
  mbdy forcemomentvec_interp blade1 c2def local_aero 60 1.0 # blade1 R=60  ;
  mbdy forcemomentvec_interp blade1 c2def local_element 50 1.0 # blade1 R=50  ;
; an example where the forces and moments are extracted at the c2def instead of the actual node:
  mbdy forcemomentvec_interp blade1 c2def blade1 5 1.0 # blade1 R= 5 ; ()
;
  dll outvec 1 1 # time;
  dll outvec 1 2 # pitch angle 1;
  dll outvec 1 3 # pitch vel 1;
  dll outvec 1 4 # pitch angle 2;
  dll outvec 1 5 # pitch vel 2;
  dll outvec 1 6 # pitch angle 3;
  dll outvec 1 7 # pitch vel 3;
  dll outvec 1 8 # gen. azi slow;
```

```
  dll outvec 1 9 # gen. speed slow;
  dll outvec 1 10 # free wind x;
  dll outvec 1 11 # free wind y;
  dll outvec 1 12 # free wind z;
  dll outvec 1 13 # gear ratio;
  dll inpvec 1 1 # Mgen slow;
  dll inpvec 1 2 # pitchref 1;
  dll inpvec 1 3 # pitchref 2;
  dll inpvec 1 4 # pitchref 3;
  dll inpvec 1 7 # F;
  dll inpvec 1 8 # Mechanical power generator [kW];
  dll inpvec 1 10 # Pitch rate [rad/s];
  dll inpvec 2 1 # pitch 1;
  dll inpvec 2 2 # pitch 2;
  dll inpvec 2 3 # pitch 3;
  dll outvec 2 1 # time;
  dll outvec 2 2 # pitchref 1;
  dll outvec 2 3 # pitchref 2;
  dll outvec 2 4 # pitchref 3;
  dll outvec 2 5 # pitch angle 1;
  dll outvec 2 6 # pitch speed 1;
  dll outvec 2 7 # pitch angle 2;
  dll outvec 2 8 # pitch speed 2;
  dll outvec 2 9 # pitch angle 3;
  dll outvec 2 10 # pitch speed 3;
end output;
;
exit;
```

B User guide for user-wind-dll

A user defined DLL can be used to provide additional wind velocity on top of what is already defined by wind input in HAWC2. During simulation, HAWC2 calls the DLL with position as argument, and the DLL must provide the wind velocity in that position on return. Apart from the position, HAWC2 also parses time and user-specified arguments to the DLL - the user-specified arguments are defined in the same output block format as is used for type2_dlls and hawc_dlls and as regular output.

B.1 Htc file input

Application of the DLL is defined inside the `begin wind` block as shown below.

```
begin wind ;
    .
    begin user_wind_dll ;
        filename 2-test.dll;
        subroutine wind_dll_getwindspeed ;
        refsys 0     ; Reference coordinates for position (in) and velocity (in/out),
                     ;   0=meteorological(default),
                     ;   1=global
        begin output ;
            general constant 1.0                    ;
            dll inpvec 1 1                          ;
            constraint bearing1 shaft_rot 1 only 2  ;
            mbdy momentvec shaft 1 1 shaft only 3   ;
        end output ;
    end user_wind_dll ;
    .
end wind
```

The output arguments that can be used inside the `begin output` block are limited `general`, `dll`, `constraint`, and `mbdy`.

B.2 DLL interface definition

The DLL subroutine is called each iteration with these arguments: - time, (double). - position vector: Dependent on the key `refsys` in the `user_wind_dll` block (see above), the position vector provided is either meteorological or global coordinates, (double(3)). - Nof arguments in the `begin output` in the `user_wind_dll` block, (nargs, integer). - Argument vector defined in the `begin output` in the `user_wind_dll` block, (double(nargs)). - Wind velocity: On input, the vector contains the wind velocity contribution from the whatever is defined in the `begin wind` block, i.e. the sum of mean wind, wind shear, etc. On output, the vector must contain the extra(!!, NOT the total) wind contribution in the `refsys` coordinate system , (double(3))

The DLL subroutine interface is defined as follows:

```
interface
    subroutine user_wind_dll_call(time, pos, nargs, args, wsp)
    !dec$ attributes c :: user_wind_dll_call
    double precision    :: time         ! time
    double precision    :: pos(3)       ! position of lookup point (refsys coordinates)
    integer             :: nargs        ! nof user arguments (provided via dll output
    block)
    double precision    :: args(nargs)  ! user arguments (provided via dll output block)
    double precision    :: wsp(3)       ! lookup windspeed,
                                            !   on input : wind velocity in <pos>
    (refsys coord.)
```

```
                                                  !   on output: user velocity contribution (refsys coord.)
    !dec$ attributes reference :: time, pos, nargs, args, wsp
    end subroutine
end interface
```

Note that the effect of tower shadow is applied after the call to the DLL.

B.2.1 FORTRAN example

```
subroutine wind_dll_getwindspeed(time,pos,nvar,var,wsp)
    !dec$ attributes c,dllexport, alias:"wind_dll_getwindspeed" :: wind_dll_getwindspeed
    !gcc$ attributes cdecl :: wind_dll_getwindspeed
    !gcc$ attributes dllexport :: wind_dll_getwindspeed
    ! variables
    integer nvar
    double precision time,pos(*),var(*),wsp(*)
    !dec$ attributes reference :: time, pos, var, wsp

    ! implementation
    print*,"nvar = ",nvar
    print*,"time = ",time
    print*,"pos  = ", pos(1:3)
    print*,"wsp  = ", wsp(1:3)
    wsp(1:3) = (/0.0, 0.0, 0.0/)
end subroutine wind_dll_getwindspeed
```

The DLL can be built from the FORTRAN code above using the GNU compiler syntax:

```
gfortran -shared -static -o <file>.dll -fno-underscoring <file>.f90
```

B.2.2 C example

```
#include <stdio.h>
__declspec(dllexport) void wind_dll_getwindspeed(double* time, double* pos, int* nvar, double* var, double* wsp)
{
    int i;
    //  implementation
    printf("nvar = %d\n", *nvar);
    printf("time = %f\n", *time);
    printf("pos  = (%f, %f, %f)\n", pos[0], pos[1], pos[2]);
    printf("wsp  = (%f, %f, %f)\n", wsp[0], wsp[1], wsp[2]);
    for (i = 0; i < 2; i++)
    {
        wsp[i] = 0.0;
    }
}
```

The DLL can be built from the C code above using the GNU compiler syntax: “‘ gcc -shared -static -o .dll .c

C Fit of structural damping

Please note that this feature is not easy to use, and some iterations must be foreseen in order to end at satisfactory result.

The aim of this feature is to develop a method to fit the damping parameters in a HAWC2 model in such a way that desired damping ratios are obtained for specified eigenmodes. Further, it is the aim that the formulation can be used in both HAWC2 and HAWCStab2.

The method is described below in Section C.1. It fits element stiffness matrices and saves them to file so that they can be used for bodies using the damping method "damping_file <damping file> ;" (where the <damping file> is generated by the method). This requires a special block inside the htc file which must be placed after the "new_htc_structure" block:

Obl.	Command name	Explanation
*	begin damping_fit ;	First line in damping fit block.
*	damping_file	Name of damping file. This file name MUST match the <damping file> used for the "damping_file" method in the "main_body" block.
	twin_bodies	The two body names given as arguments will share damping properties. This is used e.g. to specify the same damping for all the blades on the rotor. 1. Body name for 1st twin. 2. Body name for 2nd twin.
*	cmd_solver	1. Command executed by HAWC2 which does the actual fitting, (e.g. *python.exe damping_fit.py ;*). If you rely on a virtual Python environment, make sure to activate this first before running HAWC2 within this environment. Within this Python environment the `numpy` and `scipy` packages are required to be installed.
*	mode -	Repeated line for each mode to be fitted: 1. Mode number. 2. Damping ratio.
*	end damping_fit ;	Last line in damping fit block.

The example below shows the setup for fitting the damping of a single blade with requested damping ratios specified for the first six modes. 0.5% damping ratio (i.e. approx. 3% log.decr.) is requested for modes 1 and 2, 1% for modes 3 and 4, and 2% for modes 5 and 6. Note the use of the damping file (blade.dmp) in two locations which links the damping fit only to include blade damping in the fit. If other bodies were present in the example, the damping specified for those bodies would enter the total damping fit, but only the damping parameters for the blade will change the total damping.

```
;--------------------------------------------------------------------------
begin new_htc_structure;
;--------------------------------------------------------------------------
  begin main_body;
  name        blade1 ;
  type        timoschenko ;
  nbodies     10 ;
  node_distribution    c2_def;
  damping_file blade.dmp ;
  begin timoschenko_input ;
    filename ./data/DTU_10MW_RWT_Blade_st.dat;
    set 1 1 ;                set subset
```

```
  end timoschenko_input;
  begin c2_def;            Definition of centerline (main_body coordinates)
    nsec 27 ;
    sec 1       0.00000E+00       7.00600E-05       4.44089E-16       -1.45000E+01       ;
        ..
        ..
    sec       27       -8.98940E-02       -3.33685E+00       8.63655E+01       3.42796E+00       ;
    end c2_def ;
  end main_body;
;--------------------------------------------------------------------------
  begin orientation;
    begin base;
      body   blade1;
      inipos       0.0 0.0 0.0 ;        initial position of node 1
      body_eulerang 0.0 0.0 0.0;
    end base;
  end orientation;
;--------------------------------------------------------------------------
  begin constraint;
    begin fix0;  fixed to ground in translation and rotation of node 1
      body blade1;
    end fix0;
  end constraint;
end new_htc_structure;
;--------------------------------------------------------------------------
begin damping_fit ;
  damp_file blade.dmp ;
  cmd_solver C:\Users\anmh\Anaconda3\Scripts\conda.exe run python damping_fit.py ;
  mode 1 0.005 ;       Damping ratio of mode 1
  mode 2 0.005 ;                       etc.
  mode 3 0.01 ;
  mode 4 0.01 ;
  mode 5 0.02 ;
  mode 6 0.02 ;
end damping_fit ;
;--------------------------------------------------------------------------
```

A fully functional example is available for download at `https://gitlab.windenergy.dtu.dk/HAWC2Public/examples/-/tree/master/hawc2/structure/damping_fit/IEA_15MW_RWT`.

C.1 Formulation

The linearised HAWC2 EOMs are of the usual 2nd order form:

$$\mathbf{M}\,\mathbf{x} + \mathbf{C}\,\mathbf{x} + \mathbf{K}\,\mathbf{x} = \mathbf{0} \tag{C.5}$$

The solution to the undamped eigenvalue problem ($\mathbf{C} = \mathbf{0}$) are defined by the eigenvectors $\mathbf{\Gamma}$ and diagonal eigenfrequency matrix $\mathbf{\Omega}$. The eigensolution fulfills the identity $\mathbf{M\Gamma\Omega^2} = \mathbf{K\Gamma}$. By using the eigenvectors as basis, $\mathbf{x}$ can be transformed as $\mathbf{x}(\mathbf{t}) = \mathbf{\Gamma}\,\alpha(\mathbf{t})$. By using the above relations, C.5 can be manipulated as:

$$\ddot{\alpha} + \mathbf{\Gamma^{-1}M^{-1}C\Gamma}\,\alpha + \mathbf{\Omega^2}\,\alpha = \mathbf{0} \tag{C.6}$$

Note that the undamped part of C.6 is a diagonal system, and that the total set of equations can de uncoupled if the damping matrix part is also a diagonal matrix. If we choose this matrix as

$2\,\zeta\mathbf{\Omega}$ (ζ is a diagonal matrix), then the system damping matrix $\mathbf{C}$ can be calculated as

$$\mathbf{C} = \mathbf{2\,\Gamma M}\zeta\mathbf{\Omega\Gamma^{-1}} \tag{C.7}$$

Unfortunately, such a damping matrix cannot directly be used in neither HAWC2 nor in HAWCStab2, so something else must be done. Instead, the damping of one mode at a time is formulated as function of element damping matrices:

$$\ddot{\alpha}_\mathbf{i} + (\gamma_\mathbf{i}{}^\mathbf{T}\mathbf{M}\gamma_\mathbf{i})^{-1}(\gamma_\mathbf{i}{}^\mathbf{T}\mathbf{C}\gamma_\mathbf{i})\,\alpha_\mathbf{i} + \mathbf{\Omega}_\mathbf{i}^\mathbf{2}\,\alpha_\mathbf{i} = \mathbf{0} \tag{C.8}$$

where all variables with sub-script i relate to the i'th eigenmode. The damping coefficient in (C.8) must then fulfill the equation

$$(\gamma_\mathbf{i}{}^\mathbf{T}\mathbf{M}\gamma_\mathbf{i})^{-1}(\gamma_\mathbf{i}{}^\mathbf{T}\mathbf{C}\gamma_\mathbf{i}) = \mathbf{2}\zeta_\mathbf{i}\,\mathbf{\Omega_i} \tag{C.9}$$

The system damping matrix, $\mathbf{C}$, is assembled based on element damping matrices $\mathbf{c_j}$ (for the j'th element), where the element damping matrices are defined as having the same eigenvectors as the element stiffness matrices. By using this formulation, the structure only dissipates energy when it is deformed and not during rigid body motion.

$$\mathbf{c_j} = \mathbf{v_j x_j v_j^T} \tag{C.10}$$

where $\mathbf{v_j}$ is the eigenvectors of the j'th stiffness matrix (or rather the six eigen vectors that have non-zero eigenvalues) and $\mathbf{x_j}$ is a 6×6 diagonal matrix containing the unknown damping parameters.

For each eigenmode that needs to be fitted, (5) provides one equation that needs to be fulfilled, and the unknowns are the six element damping parameters, $diag(\mathbf{x_j})$, for all elements. Further, in order for the element damping matrices to be positive semi-definite, $\mathbf{x_j} \geq \mathbf{0}$ for all diagonal components $\mathbf{x_j}$ and for all elements (all j). The equations in (C.9) are linear in $\mathbf{x}$ and the (one of many!) solution is found by solving the optimization problem

$$\min_{wrt.\mathbf{x}} \left(|\mathbf{W}\,(\mathbf{A}\,\mathbf{x} - \zeta)|^2\right),\ \ s.t.\ \mathbf{x} \geq \mathbf{0} \tag{C.11}$$

where $\mathbf{x}$ are the element damping parameters for all elements collected in a vector, ζ are the (user-specified) damping ratios prescribed for the individual modes, $\mathbf{A}$ are the coefficients to $\mathbf{x}$ in accordance with (C.9), and $\mathbf{W}$ is a diagonal weighting matrix which is included in order to weigh the individual eigenmodes in the optimization.

C.2 HAWC2 implementation

Currently, the solution of (C.11) is handled by an external call to a python script outside of HAWC2. This means that HAWC2 calculates the matrices and vectors in (C.11) and exports those to a binary file (currently named *'dfit_a.bin'*). This binary file is then handled in a Python script that reads the system, solves (C.11) for $\mathbf{x}$ and writes back the solution to file (currently named *'dfit_x.bin'*). This solution is then read back into HAWC2 and the resulting element damping matrices are calculated and written to file for subsequent use in HAWC2 simulations.

Note that even though only a few of the total number of eigenmodes have prescribed damping ratios (specified in the htc-file), all eigenmodes are included in the outputted binary file, however, the components in $\mathbf{W}$ associated with non-prescribed modes are all set to zero.

The Python script is listed below from which the individual binary file formats can be deduced, if needed. This script is part of the distributed HAWC2 files.

```
#------------------------------------------------------------------------
# -*- coding: utf-8 -*-
"""
Damping fit for HAWC2

This script finds the parameters for structural HAWC2 damping type
"damp_file", based on the mode damping matrix, A, calculated by HAWC2
and written to file "dfit_a.bin".

Each row of the A matrix corresponds to a mode shape in the HAWC2 model,
ordered in increasing order of eigenfrequency, i.e. first row corresponds to
the mode with the lowest eigenfrequency. By multiplication with the damping
parameter vector, x, gives the damping rati0 vector, d = (A*x).

The purpose of this script is then to find the best fit of x which gives the
specified damping ratio for the individual modes using the constraint that
x>0 for all x.

The A matrix contains all modes, and not all modes can be fitted for any
damping level. Normally the first (say 10) modes are of interest. This is
handled by the weighting vector, w, below. See code below for further details.

"""

import numpy as np
import struct
from scipy.optimize import nnls

def damping_fit():

    wmin = 1.e-6

    # Read A matrix from file
    f=open('dfit_a.bin','rb')
    (nr,nc) = struct.unpack('ii',f.read(8))
    ntot = nr*nc
    data = np.zeros(ntot,dtype=np.dtype('f8'))
    for i in range(ntot):
        (data[i],) = struct.unpack('d',f.read(8))
    A = np.reshape(data,[nr,nc], order='F')

    # Read target damping for optimization
    d = np.zeros(nr,dtype=np.dtype('f8'))
    for i in range(nr):
        (d[i],) = struct.unpack('d',f.read(8))
    w = np.zeros(nr,dtype=np.dtype('f8'))
    for i in range(nr):
        (w[i],) = struct.unpack('d',f.read(8))
        if w[i] == 0.0:
            w[i] = wmin
    f.close()

    # Solve
    res = nnls(np.matmul(np.diag(w),A), np.matmul(np.diag(w),d))

    # Write results to file
    f = open('dfit_x.bin','wb')
    f.write(np.array([nc,1],dtype='i4'))
    f.write(res[0])
    f.close()

    # Check solution
    dfit = np.matmul(A,res[0])
    print(('*'+'{0:1s}'*36+'*').format('*'))
```

```python
    print('*{:^36s}*'.format('Damping fit result'))
    print(('*'+'{0:1s}'*36+'*').format('*'))
    print('*{:^8s}{:^14s}{:^14s}*'.format('Mode','Target','Fit'))
    for i in range(nr):
        if w[i] > wmin:
            print('*{:^8d}{:^14.3e}{:^14.3e}*'.format(i+1,d[i],dfit[i]))
    print(('*'+'{0:1s}'*36+'*').format('*'))

    return res

#-----------
# DO IT....
#-----------
res = damping_fit()
#------------------------------------------------------------------------
```

C.3 Usage considerations

C.3.1 Consistently use matched input and damping file

The result of the structural damping fitting procedure is a main body element damping matrix file that will match the user defined damping for the relevant modes. This file is specific for a given combination of nodes, number of bodies and structural input (st-file). If any changes are made in either of these inputs the element damping matrix file will have to be redefined based on the procedure outlined here. Users are especially cautioned to carefully track that the number of bodies used for generating the damping fit is also the same number of bodies used in subsequent simulations.

C.3.2 Tune on full or main body only models

It is more likely to obtain a good damping fit for many frequencies when tuning the damping for a HAWC2 model containing only the main body of interest. When a model with several main bodies is used (tower, blades, etc) the optimisation problem becomes inherently more difficult to solve. When using multiple main bodies, make sure to verify that the targeted damping ratios in the `damping_fit` section relate to the total systems modes (1st and 2nd modes likely to be the tower, etc), as opposed to when using a model that only contains the main body of interest. The user is responsible for tracking which mode number relates to which body. For example, fitting the damping for tower modes while only adjusting the damping coefficients related to the blades is not likely to give meaningful results. It is therefore recommended to only list/target mode numbers of the body at interest, and leave out the others (especially rigid body modes) in the `damping_fit` section.

C.3.3 Number of modes to target

When fitting to a low number of modes a very good result can be expected. The more modes a user attempts to fit a damping value to, the more difficult the trade-off becomes. In those cases an advanced user could consider changing the weights $\mathbf{W}$ in the example script `damping_fit.py` (defined as `w`, see above) to obtain a specific trade-off in which some modes are allowed to differ more compared to others with respect to the requested target values.

D ESYSMooring user guide

ESYSMooring is the DLL that allows you to model mooring lines and guy wires in HAWC2.

This DLL implements the equations of motion of a mooring line element. An extended description of the mathematical model can be found in Hansen and Kallesøe [2]. Via the ESYSMooring, a user can specify and define two main components, that univocally define a mooring system: the mooring lines themselves (named *elasticbar*) and a set of *constraints* where the mooring line can be fixed either to the global reference system, to another node of the HAWC2 structure, or to another mooring line, to generate more complex mooring geometries. We will hereafter see how to specify lines and how to connect them through constraints.

D.1 Definition of the mooring line

```
begin ext_sys                          ;
  module    ElasticBar                   ;
  name      <line name>                  ;
  dll               ESYSMooring.dll      ;
  ndata <n>                              ;
  data nelem <n>                         ;
  data mass <ma> <mw>                    ;
  data start_pos <X> <Y> <Z>             ;
  data end_pos <X> <Y> <Z>               ;
  data cdp_cdl_cm <cdp> <cdl> <cm>       ;
  data axial_stiff <EA>                  ;
  data read_write_initcond_file <fname>  ;
  data read_write_initcond <rd> <wr>     ;
  data bottom_prop <z0> <d0> <dr>        ;
  data damping_ratio <sdr>               ;
  data apply_wave_forces <wa>            ;
  data apply_wind_forces <wi>            ;
  data output position <node>            ;
  data output force <ielem>              ;
  data output strain <ielem>             ;
  data mass_summary <file>               ;
  data end                               ;
end   ext_sys
```

Obl.	Command name	Explanation
*	begin ext_sys ;	First line in ESYSMooring.
	module ElasticBar ;	Module ID (Fixed)
	name <line name>	Name of system, used as a reference. It becomes especially useful when you have more than one mooring system.
	dll ESYSMooring.dll	DLL file name (including path)
	ndata <n>	Number of data input lines below, including the "data end" line. Remember that commented lines are excluded from the count.
	data nelem <n>	Numer of elements by which we discretize the mooring line
	data mass <ma> <mw>	Mass per length [kg/m]. 1. <ma> : mass per length in air

[2] A.M.Hansen and B.Kallesøe "Detailed and reduced models of dynamic mooring systems", In: Hansen, M. H., and Zahle, F. (2011). Aeroelastic Optimization of MW Wind Turbines. Roskilde: Danmarks Tekniske Universitet, Risø Nationallaboratoriet for Bæredygtig Energi. Denmark. Forskningscenter Risoe. Risoe-R; No. 1803(EN), link

Obl.	Command name	Explanation
		2. <mw> : mass per length in water, normally computed as mw - rho_water*A, where A is the cross sectional area of the line
	data start_pos <X> <Y> <Z>	X-Y-Z-coordinate for first node (global coordinates)
	data end_pos <X> <Y> <Z>	X-Y-Z-coordinate for last node (global coordinates)
	data cdp_cdl_cm <cdp> <cdl> <cm>	The hydrodynamic coefficients of the line. For drag, the velocity in each node is decomposed into a perpendicular and an axial component, and the force/length in each of the directions is calculated as: q = cd*abs(v)*v, so cd-units=$[N/m/(m/s)^2]$. The same principle is used for cm, except only the perpendicular direction is active, ie. cm-unit $[N/m/(m/s^2)]$ 1. <cdp> Drag coefficient perpendicular to the element. 2. <cdl> Drag coefficient along the element. 3. <cm> Mass coefficient.
	data axial_stiff <EA_1> <EA_2>...<EA_N>	Hyper-elastic axial stiffness of line [N] where the axial force, T is related to the Green's strain, ϵ, as $T = \sum_{i=1}^{N}(EA_i \epsilon^i)$.
	data read_write_initcond_file <fname>	File name where initial conditions are read/written to (default="ESYSMooring_init.dat")
	data read_write_initcond <rd> <wr>	Read/write position of the nodes. If <rd>=1, the initial positions of the nodes are read from file ESYSMooring_init.dat ; at the start of simulation. If <wr>=1, the node positions are written to same file when simulation ends.
	data bottom_prop <z0> <d0> <dr>	Bottom properties. 1. <z0> [m] is the Z coordinate of the bottom (in global coordinates) 2. <d0> [m] is the penetration depth into the bottom. When an element lies on the bottom exposed to gravity and buoyancy (used to define the bottom sprinf stiffness) 3. <dr> [-] defines the bottom damper system as the damping ratio of the element lying on the bottom. ; NOTE: IF BOTTOM PROPERTIES ARE NOT NEEDED, MAKE <z0> SUFFICIENTLY LARGE TO AVOID BOTTOM CONTACT.
	data damping_ratio <sdr>	Structural damping ratio, defined as the damping ratio of 1st axial mode of the free-free line [-]
	data apply_wave_forces <wa>	If <wa>=1, wave kinematics is read and used to calculate drag/added mass forces. This option is mutually exclusive with apply_wind_forces
	data apply_wind_forces <wi>	If <wi>=1, wind speed read and used to calculate drag/added mass forces.
	data output position <node>	Write global position of node number <node> to output file. (only if "ESYS <line name> ;" is defined in output block of htc file.)
	data output force <ielem>	Write force in element number <ielem> to output file. (only if "ESYS <line name> ;" is defined in output block of htc file.)
	data output strain <ielem>	Write strain in element number <ielem> to output file. (only if "ESYS <line name> ;" is defined in output block of htc file.)
	data mass_summary <file>	Write summary of all ElasticBar objects to <file>
	data creep_time <tstart>	Time [s] when creep models are activated (default=0s).
	data creep_kc <K> <tau>	Creep model consisting of a spring/damper system (in series) which act in parallel with the "axial_stiff" spring. The spring has the stiffness <K> [N] and the damping is defined via the time constant <tau>=C/K [s]. For each "creep_kc" line, one new spring/damper system is added parallel with the other systems.

Obl.	Command name	Explanation
	data pretension <T>	Pre-tension [N]. The un-stretched length of the line is adjusted (relative to the length between start and end position) according to the strain caused by the pre-tension. Initial position of the nodes are distributed between start and end positions so that the initial pre-tension in each element is equal to <T>.
	data end	MUST be the last line in the input block

D.2 Constraints

There are 4 types of constraints, that are able to describe different ways to anchor the mooring lines.

- Bar fixed to bar: a mooring element is fixed to another mooring element
- Bar fixed to global: a mooring element is fixed to a global reference
- Bar fixed to body: a mooring line is fixed to an HAWC2 beam node
- Bar fixed to body relative: a mooring line is fixed to an HAWC2 beam mode, but is possible to specify an offset from a certain node.

Each one of those has a slightly different interface.

D.2.1 Bar fixed to bar (*cstrbarfixedtobar*)

```
  begin   dll                                         ;
  dll     .\ESYSMooring.DLL                       ;
  init    cstrbarfixedtobar_init      ;
  update  cstrbarfixedtobar_update    ;   Update procedure name
  neq     3                               ;       NOF constraint equations
  nbodies 0                           ;   NOF bodies involved
  nesys   2                           ;   NOF ESYSs involved
  esys_node       line1    10             ;   ESYS name and node number for 1st node
  esys_node       line2     1             ;   ESYS name and node number for 2nd node
end     dll                                 ;
```

Obl.	Command name	Explanation
*	begin dll ;	First line in ESYSMooring.
	dll <name>	DLL name
	init cstrbarfixedtobar_init	Init procedure name. Not to be altered
	update cstrbarfixedtobar_update	Update procedure name. Not to be altered
	neq <n>	Number of constraint equations, normally 3.
	nbodies <n>	Number of bodies involved. This is zero for this type of constraint, as it's a line-to-line constraint.
	nesys <n>	Number of esys involved. This is different from zero for this type of constraint, normally 2 if two lines are involved.
	esys_node <name> <node>	ESYS name and node number for a node. This command needs to be specified more than once, for all the lines involved. <name> is the name specified in the definition block for the line under consideration, see subsection D.1. <node> is an integer specifying the node nr.

D.2.2 Bar fixed to bar (*cstrbarfixedtoglobal*)

```
  begin   dll                     ;
  dll     .\ESYSMooring.DLL                        ;       DLL name
  init    cstrbarfixedtoglobal_init   ;   Init procedure name
  update  cstrbarfixedtoglobal_update ;   Update procedure name
  neq     3                               ;       NOF constraint equations
  nbodies 0                           ;   NOF bodies involved
  nesys   1                           ;   NOF ESYSs involved
  esys_node       line1_1  1              ;   ESYS name and node number
end     dll                                 ;
```

Obl.	Command name	Explanation
*	begin dll ;	First line in ESYSMooring.
	dll <name>	DLL name
	init cstrbarfixedtoglobal_init	Init procedure name. Not to be altered
	update cstrbarfixedtoglobal_update	Update procedure name. Not to be altered
	neq <n>	Number of constraint equations, normally 3.
	nbodies <n>	Number of bodies involved. This is zero for this type of constraint, as the line is fixed to the global reference system.
	nesys <n>	Number of esys involved. This is 1 for this type of constraint.
	esys_node <name> <node>	ESYS name and node number for a node. This command needs to be specified once for every node that is considered fixed to the global reference system. <name> is the one specified in the line definition block, see subsection D.1. <node> is an integer specifying the node nr.

D.2.3 Bar fixed to bar (*cstrbarfixedtobody*)

```
  begin   dll                     ;
  ID      100.0                                    ;       time to satisfy constraint [sec]
  dll     .\ESYSMooring.DLL                                ;       DLL name
  init    cstrbarsfixedtobody_init            ;   Init procedure name
  update  cstrbarsfixedtobody_update          ;   Update procedure name
  neq     3                                        ;       NOF constraint equations
  nbodies 1                                   ;   NOF bodies involved
  nesys   1                                   ;   NOF ESYSs involved
  mbdy_node       arm1    2                        ;       Bode name and node number
  esys_node       line1_1 31                       ;   ESYS name and node number
end     dll
```

Obl.	Command name	Explanation
*	begin dll ;	First line in ESYSMooring.
	ID <time>	Time at which the constraint should be satisfied. This is useful when initializing the mooring system, see subsection D.3.
	dll <name>	DLL name
	init cstrbarsfixedtobody_init	Init procedure name. Not to be altered
	update cstrbarsfixedtobody_update	Update procedure name. Not to be altered
	neq <n>	Number of constraint equations, normally 3.

Obl.	Command name	Explanation
	nbodies <n>	Number of bodies involved. This is different from zero for this type of constraint, as there should at least be a body involved.
	nesys <n>	Number of esys involved. This is 1 or more for this type of constraint.
	esys_node <name> <node>	ESYS name and node number for a node. This command needs to be specified once for each node of the linex involved in the constraint. <name> is the one specified in the line definition block, see subsection D.1. <node> is an integer specifying the node nr.
	nbodies <n>	Number of bodies involved in the constraint
	mbdy_node <name> <node>	multibody name and node number for a node. This command needs to be specified once for each node of the multibody involved in the constraint. <name> is the one specified in the multibody definition block. <node> is an integer specifying the node nr.

D.2.4 Bar fixed to bar (*cstrbarfixedtobodyrelative*)

```
  begin   dll                      ;
  ID      0.0 1.0 0.0 100.0                        ;       vector from body node (in body coord
  dll     .\ESYSMooring.DLL                                ;       DLL name
  init    cstrbarsfixedtobodyrelative_init    ;   Init procedure name
  update  cstrbarsfixedtobodyrelative_update  ;   Update procedure name
  neq     3                                        ;       NOF constraint equations
  nbodies 1                                   ;   NOF bodies involved
  nesys   1                                   ;   NOF ESYSs involved
  mbdy_node       arm1    2                        ;       Bode name and node number
  esys_node       line1_1 31                       ;   ESYS name and node number
end     dll
```

Obl.	Command name	Explanation
*	begin dll ;	First line in ESYSMooring.
	ID <x> <y> <z> <time>	Vector from the body node (in body coordinates), units [m] and time [sec] at which the constraint should be satisfied. This is useful when initializing the mooring system, see subsection D.3.
	dll <name>	DLL name
	init cstrbarsfixedtobody_init	Init procedure name. Not to be altered
	update cstrbarsfixedtobody_update	Update procedure name. Not to be altered
	neq <n>	Number of constraint equations, normally 3.
	nbodies <n>	Number of bodies involved. This is different from zero for this type of constraint, as there should at least be a body involved.
	nesys <n>	Number of esys involved. This is 1 or more for this type of constraint.
	esys_node <name> <node>	ESYS name and node number for a node. This command needs to be specified once for each node of the linex involved in the constraint. <name> is the one specified in the line definition block, see subsection D.1. <node> is an integer specifying the node nr.
	nbodies <n>	Number of bodies involved in the constraint

Obl.	Command name	Explanation
	mbdy_node <name> <node>	multibody name and node number for a node. This command needs to be specified once for each node of the multibody involved in the constraint. <name> is the one specified in the multibody definition block. <node> is an integer specifying the node nr.

D.3 Procedure for mooring initialization

When initializing a simulation with a mooring system, it is often important to initialize the connection with the mooring system as well. The initial position and tension of the lines should be as close as possible to the equilibrium position, otherwise quite large oscillations can be triggered at the beginning of the simulation, which, depending on the natural frequencies of the system and on the damping level, can last for many seconds, unnecessarily increasing the transient time and possibly posing threats to the stability and convergence of the simulation.

Unless the configuration of the lines is simple (e.g. a vertical tendon or a taut line with a certain angle), the initial position of the line elements is normally difficult to precompute. The strategy that is here suggested therefore consists in two steps:

1. Run a line initialization simulation and store the final position of the lines
2. Read in the stored line position and use it as initial condition for the mooring system in the production simulation

An example on the procedure is available in our public example library here. The two steps are here described in more detail:

1. Line initialization: In the line initialization simulation, we start with the lines in a simple, unloaded position. For a catenary line, it could be a position for which it is lying flat on the seabed. We then make use of the time option in the *cstrbarfixedtobody* and *cstrbarfixedtobodyrelative* constraints, see subsubsection D.2.3 and subsubsection D.2.4 to fix a line to a body after a certain specified time. This will allow the line to move to the specified position and assume a natural position, that is then physically accurate as it will be computed by the structural solver itself. The time at which the constraint is satisfied needs to be long enough so that the structural accelerations of the lines is small. If not, traveling waves can be generated in the line, which may take a long time to damp out, artificially increasing the transient. This initialization simulation is best run without water and wind forces. We then use the option `data read_write_initcond 0 1` in the line initialization to write a file containing the position of the nodes of the line at final position, i.e. at the end of the simulation time.

2. Production run: The final position of the files stored in the above mentioned file will consist in the initial condition of the lines in the production simulation. With this respect, the command needs now to be changed to `data read_write_initcond 1 0` to signify that the initial condition is now read and not written to file. The time in the `ID <x> <y> <z> <time>` and `ID <time>` respectively for the *fixed to body relative* and *fixed to body* constraints can now be set to a small value, ideally to zero. However, small discrepancies are to be expected between the final position of the line in the initialization simulation and the required initial position in the production run, so a value different from zero may be used here.

D.3.1 Important notes for the line initialization procedure

- The initialization and production simulation do not need to be the same, i.e. to have the same number of bodies. As far as the final position of the line is consistent, the initialization simulation could be run with a single dummy body.

- It is suggested to fix all present multibodies to the global reference system when running the initialization simulation, and possibly to turn off gravity on them, but not the one for the lines, as f.ex. in catenary mooring we do want the lines to assume a natural shape, driven by their own weight.
- It is suggested to switch off the wave and wind loads for the lines in the initialization simulation, as this could lead to convergence issues.
- The simulation time for the initialization simulation needs to be larger or equal to the time at which the constraint is satisfied.

D.3.2 Format of the line initialization file

The file that is written by `ESYSMooring` initialization routine is quite simple. In practice, it stores the coordinates of the nodes sequentially, stasrting from node 1 to the last node, in global coordinates. If the same file is specified for all the lines via the `data read_write_initcond_file <fname> ;` command, then the node coordinates are written in the same order in which the lines are defined. If the file name is not provided,the default file name is used, `ESYSMooring_init.dat`.

Assuming we have `m` lines, each one with `n` nodes, the format of the file is therefore:

```
l1_x1 l1_y1 l1_z1
l1_x2 l1_y2 l1_z2
...
l1_xn l1_yn l1_zn
l2_x1 l2_y1 l2_z1
l2_x2 l2_y2 l2_z2
...
lm_xn lm_yn lm_zn
```

where `l1_x1` is the x-coordinate for the first node of the first line, while `lm_yn` is the y-coordinate of the n-th node of the m-th line.

If particular initial conditions of the lines are needed, the coordinates of the nodes can f.ex. be generated via a scripting language and then written to file in this format. If properly formatted, `ESYSMooring` will be able to load them in.

D.4 List of Channels in the HAWC2 output

To switch on the output for a generic line named `lineX` the following line needs to be specified in the HAWC2 output section

```
esys lineX;
```

In the HAWC2 output files, the results for the mooring line are stored according to the following format. The output comes in blocks of 4 values, which are the X,Y,Z position of a mooring node and the axial tension experienced at that node. For a given mooring line `lineX` discretized in N elements, the line will have N+1 nodes and the output channels will be sorted like shown below. All coordinates are given in HAWC2's global coordinate system.

```
ESYS lineX SENSOR 1 X position of  node 1
ESYS lineX SENSOR 2 Y position of  node 1
ESYS lineX SENSOR 3 Z position of node 1
ESYS lineX SENSOR 4 Tension at  node 1
```

```
...

ESYS lineX SENSOR 4*i-3 X position of  node i
ESYS lineX SENSOR 4*i-2 Y position of  node i
ESYS lineX SENSOR 4*i-1  Z position of node i
ESYS lineX SENSOR 4*i Tension at  node i

...

ESYS lineX SENSOR 4*(N+1)-3 X position of  node N+1
ESYS lineX SENSOR 4*(N+1)-2 Y position of  node N+1
ESYS lineX SENSOR 4*(N+1)-1  Z position of node N+1
ESYS lineX SENSOR 4*(N+1) Tension at  node N+1
```

E ESYSWAMIT user guide

When modelling floating structures in waves, it is common to obtain the hydrodynamic properties through radiation-diffraction theory. One of the most widely used commercial codes for such purpose is WAMIT, developed at MIT.

HAWC2 can handle WAMIT outputs and use them to represent hydrodynamic loads on e.g. floating wind turbines. The interface that couples the WAMIT output to the time-domain HAWC2 model is called ESYSWAMIT. This guide explains the ESYSWAMIT interface, including coordinate systems, how to set up the inputs, and the list of output channels. The reader is assumed to have some knowledge of radiation-diffraction theory in general, and some experience with WAMIT in particular. In the WAMIT website there are several resources including manuals, theory and more.

E.1 Coordinate systems

WAMIT, ESYSWAMIT and HAWC2 all use different global coordinate systems, as illustrated in Figure 11.

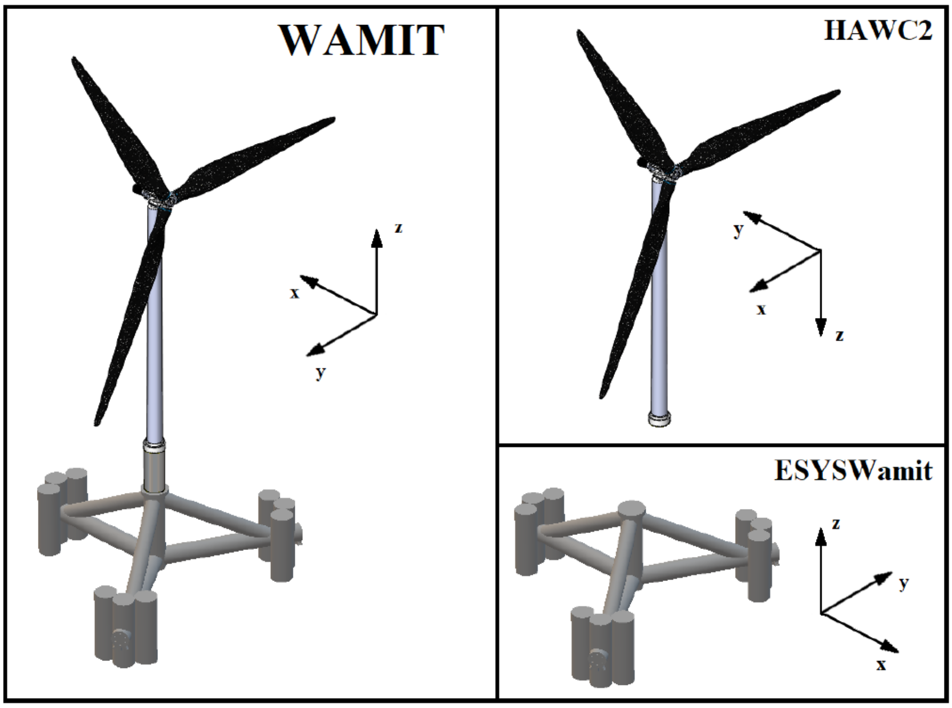

Figure 11: Different coordinate systems. The wave propagates in the positive y direction in the HAWC2 coordinate system.

Due to the different coordinate systems, the same wave heading direction β (deg) is defined differently and according to:

$$\beta_{\mathrm{ESYSWAMIT}} = \beta_{\mathrm{WAMIT}} - 180 \tag{E.12}$$

$$\beta_{\mathrm{HAWC2}} = -\beta_{\mathrm{WAMIT}} \tag{E.13}$$

For example, a 30 deg wave heading in WAMIT would correspond to -30 deg in HAWC2 and to -150 deg (or 210 deg) in ESYSWAMIT.

E.2 Running WAMIT

Instructions on how to run a WAMIT analysis are out of the scope of this guide. However, here we point at specific points to take into account when running a WAMIT analysis with the purpose of coupling it to HAWC2.

- **Center of gravity**: the hydrostatic stiffness of a floating body in pitch and roll depends on the z coordinate of the global center of gravity, z_g. However, the hydrostatic properties are internally corrected by ESYSWAMIT to include the effect of the global z_g (including tower, rotor, etc.). Thus, for consistency the WAMIT analysis should be carried out with $z_g = 0$.
- **Coordinate system**: for the reasons explained in Section E.1, the floater in the WAMIT setup must be rotated 180 deg around the z axis. Consequently, the desired wave headings must be offset according to (E.12). For example, if the original WAMIT analysis was to be carried out for $\beta_{WAMIT} = 0$, after rotating the floater in WAMIT by 180 deg around z the analysis should be carried out for $\beta_{WAMIT} = 180$.

Once the WAMIT analysis is completed, the following files will be needed by ESYSWAMIT:

- The *.hst* file, which contains the hydrostatic restoring matrix.
- The *.1* file, which contains the frequency-dependent radiation matrices (added mass and damping).
- The *.3* file, which contains the frequency- and wave direction-dependent transfer function from free-surface elevation to wave loads.

For rapid visualization of WAMIT panels and output data, we recommend the open-source tool BEMRosetta.

E.3 Running HAWC2 with ESYSWAMIT

Obl.	Command name	Explanation
*	begin ext_sys	First line in ESYSWAMIT.
*	module ESYSWamit	Module ID (fixed)
*	name floater	Name of system used as reference
*	dll esyswamit.dll	DLL file
*	ndata <n>	Number of data input lines below including "data END"
*	data WAMIT_FILE <s>	path to WAMIT files
*	data GRAVITY <g>	Gravity acceleration [m/s^2]
*	data DENSITY <ρ>	Water density [kg/m^3]
*	data TIME_STEP <dt>	Global time step [s]
*	data MASS <m>	Mass of floating substructure (including ballast) [kg]
*	data COG <x> <y> <z>	Center of gravity coordinates [m]
*	data BUOY <F_B>	Buoyancy force [N]
*	data COB_XY <x> <y>	Center of Buoyancy (x,y) coordinates [m]
*	data RIJ_COG <i> <j> <RIJ>	Radii of gyration (relative to COG) J(i,j) = MASS * ABS(RIJ) * RIJ
*	data INI_POS <x> <y> <z>	Initial position [m]
*	data INIT_ROT <x> <y> <z>	Initial rotation [deg]
*	data STIF <i> <j> <K(i,j)>	Linear stiffness coefficient, so that the external FORCE(i) += -K(i,j)*X(j)

Obl.	Command name	Explanation
*	data DAMP <i> <j> <C(i,j)>	Linear drag/damping coefficient, so that the external FORCE(i) += -C(i,j)*V(j)
*	data QUAD_DRAG <i> <j> <QC(i,j)>	Quadratic drag coefficient, so that the external FORCE(i) += -QC(i,j)*ABS(V(j))*V(j)
*	data IRF_TIME_SPAN <T_irf>	Truncation time for radiation/diffraction IRF functions [s]. Note that both the first and last 2*IRF_TIME_SPAN should be discarded from the simulation.
*	data WAVE_DIR <beta>	Wave direction (0 deg: Going in the X-direction, 90 going in in Y-direction, etc.) (Default = 0 deg)
*	data DUMP_FILE_PREFIX <s>	prefix for dump of radiation/diffraction files
*	data DIFFRACTION_METHOD <s>	Calculation method of diffraction force. Options:
*		"IRF_0" = convolution using wave at the initial position (default)
*		"IRF_1" = convolution using wave at the instantaneous position
*		"FFT_0" = pre-generated using IFFT
*	data INCLUDE_QTF <SUM> <DIFF> <fcut>	Include sum-frequency QTF; Include difference-frequency QTF; Cut-off Frequency
*	data END	MUST be the last line in the input block
*	end ext_sys	Last line in ESYSWAMIT.

E.4 Adding drag loads

If inertia loads on a submerged member are already modelled through WAMIT, then HAWC2 must only add viscous drag loads through the Morison equation. To disable the inertia Morison loads, the following must be done in the corresponding `sec` command of the `hydro_element` block:

Column	Description	Value
2	added mass coefficient, C_a	-1
4	cross-sectional area, A	$\frac{\pi}{4}D^2$
5	cross-sectional area for C_a, A_r	$\frac{\pi}{4}D^2$
6	width or diameter, D	D
9	axial added mass coefficient, $C_{a,ax}$	0
11	internal cross-sectional area, S_i	$\frac{\pi}{4}D^2$

E.5 Floater visualization

It is now possible to visualize the floater in the HAWC2Visualization tool. HAWC2 currently supports only one mesh format, namely the `.stl` binary files. A specification for the format is available f.ex. here. You can easily export the geometry from any CAD program. If a different mesh format is required, please file a feature request.

For a successful use of this functionality, it must be noted that:

- The mesh coordinates need to be stored in the WAMIT coordinate system, see Figure 11 for further specifications.
- The `.stl` file needs to have the same name of the files specified via the `data WAMIT_FILE <s>`

command.

- The file needs to be in the folder *before* the simulation is run, as the ESYSWamit is storing the coordinates of the mesh in the HDF5 file produced by the `visualization` command from the `simulation` block.
- To visualize the floater, you need to have version 0.8.1 of the HAWC2Visualization tool, and at least version 12.9.15 of HAWC2MB.

E.6 ESYSWAMIT output channels

The ESYSWAMIT output comes in blocks of 6 corresponding to the 6 states (3 displacements and 3 rotations) of the floater, in the following order: floater motion (displacement, velocity, acceleration), loads (radiation, diffraction, sum QTF, diff QTF, total QTF, constraint, drag), and free-surface elevation.

The QTF channels only exist if the QTF option is enabled. The constraint force is the sum all external constraint forces, e.g. if you have 3 mooring lines and a tower structure connected, it will be the sum of those four force/moment contributions. In total one would have 6×7+1=43 channels if QTF is disabled (see Section E.6.1), or 6×10+1=61 channels if QTF is enabled (see Section E.6.2).

Note also that the ESYSWAMIT output is given in the ESYSWAMIT coordinate system, which is different from the HAWC2 coordinate system.

E.6.1 Channel list without QTF

```
ESYS floater SENSOR 1 surge  displacement
ESYS floater SENSOR 2 sway   displacement
ESYS floater SENSOR 3 heave  displacement
ESYS floater SENSOR 4 roll   displacement
ESYS floater SENSOR 5 pitch  displacement
ESYS floater SENSOR 6 yaw    displacement

ESYS floater SENSOR 7 surge  velocity
ESYS floater SENSOR 8 sway   velocity
ESYS floater SENSOR 9 heave  velocity
ESYS floater SENSOR 10 roll   velocity
ESYS floater SENSOR 11 pitch  velocity
ESYS floater SENSOR 12 yaw    velocity

ESYS floater SENSOR 13 surge  acceleration
ESYS floater SENSOR 14 sway   acceleration
ESYS floater SENSOR 15 heave  acceleration
ESYS floater SENSOR 16 roll   acceleration
ESYS floater SENSOR 17 pitch  acceleration
ESYS floater SENSOR 18 yaw    acceleration

ESYS floater SENSOR 19 surge  radiation force
ESYS floater SENSOR 20 sway   radiation force
ESYS floater SENSOR 21 heave  radiation force
ESYS floater SENSOR 22 roll   radiation moment
ESYS floater SENSOR 23 pitch  radiation moment
ESYS floater SENSOR 24 yaw    radiation moment
```

```
ESYS floater SENSOR 25 surge  diffraction force
ESYS floater SENSOR 26 sway   diffraction force
ESYS floater SENSOR 27 heave  diffraction force
ESYS floater SENSOR 28 roll   diffraction moment
ESYS floater SENSOR 29 pitch  diffraction moment
ESYS floater SENSOR 30 yaw    diffraction moment

ESYS floater SENSOR 31 surge  constraint force
ESYS floater SENSOR 32 sway   constraint force
ESYS floater SENSOR 33 heave  constraint force
ESYS floater SENSOR 34 roll   constraint moment
ESYS floater SENSOR 35 pitch  constraint moment
ESYS floater SENSOR 36 yaw    constraint moment

ESYS floater SENSOR 37 free-surface elevation
```

E.6.2 Channel list with QTF

```
ESYS floater SENSOR 1 surge  displacement
ESYS floater SENSOR 2 sway   displacement
ESYS floater SENSOR 3 heave  displacement
ESYS floater SENSOR 4 roll   displacement
ESYS floater SENSOR 5 pitch  displacement
ESYS floater SENSOR 6 yaw    displacement

ESYS floater SENSOR 7 surge  velocity
ESYS floater SENSOR 8 sway   velocity
ESYS floater SENSOR 9 heave  velocity
ESYS floater SENSOR 10 roll   velocity
ESYS floater SENSOR 11 pitch  velocity
ESYS floater SENSOR 12 yaw    velocity

ESYS floater SENSOR 13 surge  acceleration
ESYS floater SENSOR 14 sway   acceleration
ESYS floater SENSOR 15 heave  acceleration
ESYS floater SENSOR 16 roll   acceleration
ESYS floater SENSOR 17 pitch  acceleration
ESYS floater SENSOR 18 yaw    acceleration

ESYS floater SENSOR 19 surge  radiation force
ESYS floater SENSOR 20 sway   radiation force
ESYS floater SENSOR 21 heave  radiation force
ESYS floater SENSOR 22 roll   radiation moment
ESYS floater SENSOR 23 pitch  radiation moment
ESYS floater SENSOR 24 yaw    radiation moment

ESYS floater SENSOR 25 surge  diffraction force
ESYS floater SENSOR 26 sway   diffraction force
ESYS floater SENSOR 27 heave  diffraction force
ESYS floater SENSOR 28 roll   diffraction moment
ESYS floater SENSOR 29 pitch  diffraction moment
ESYS floater SENSOR 30 yaw    diffraction moment
```

```
ESYS floater SENSOR 31 surge  sum QTF force
ESYS floater SENSOR 32 sway   sum QTF force
ESYS floater SENSOR 33 heave  sum QTF force
ESYS floater SENSOR 34 roll   sum QTF moment
ESYS floater SENSOR 35 pitch  sum QTF moment
ESYS floater SENSOR 36 yaw    sum QTF moment

ESYS floater SENSOR 37 free-surface elevation

ESYS floater SENSOR 38 surge  diff QTF force
ESYS floater SENSOR 39 sway   diff QTF force
ESYS floater SENSOR 40 heave  diff QTF force
ESYS floater SENSOR 41 roll   diff QTF moment
ESYS floater SENSOR 42 pitch  diff QTF moment
ESYS floater SENSOR 43 yaw    diff QTF moment

ESYS floater SENSOR 44 surge  total QTF force
ESYS floater SENSOR 45 sway   total QTF force
ESYS floater SENSOR 46 heave  total QTF force
ESYS floater SENSOR 47 roll   total QTF moment
ESYS floater SENSOR 48 pitch  total QTF moment
ESYS floater SENSOR 49 yaw    total QTF moment

ESYS floater SENSOR 50 surge  constraint force
ESYS floater SENSOR 51 sway   constraint force
ESYS floater SENSOR 52 heave  constraint force
ESYS floater SENSOR 53 roll   constraint moment
ESYS floater SENSOR 54 pitch  constraint moment
ESYS floater SENSOR 55 yaw    constraint moment

ESYS floater SENSOR 56 surge  drag force
ESYS floater SENSOR 57 sway   drag force
ESYS floater SENSOR 58 heave  drag force
ESYS floater SENSOR 59 roll   drag moment
ESYS floater SENSOR 60 pitch  drag moment
ESYS floater SENSOR 61 yaw    drag moment
```

F Code Version Data

The release notes from all previous HAWC2 releases are included as a text file in the all-in-one download package available on `http://tools.windenergy.dtu.dk/HAWC2/downloads`.

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