Calculation of Buoyancy on a Marine Hydrokinetic Turbine in AeroDyn

Adapted from theory developed by Matt Hall and Jason Jonkman for calculating buoyancy on floating offshore wind turbine platforms in HydroDyn

**GENERAL CONSIDERATIONS**

This implementation plan details changes to OpenFAST to model buoyancy on the blades, tower, hub, and nacelle of a bottom-mounted (i.e., fixed) marine hydrokinetic (MHK) turbine. Changes will be made primarily in the AeroDyn module. Buoyant loads will be calculated in the AD\_CalcOutput subroutine and added to the previously calculated hydrodynamic loads.

**Blades and Tower**

The blades and tower are modeled as tapered cylinders. Loads are estimated by breaking each member (i.e., blade or tower) into discrete elements and integrating the hydrostatic pressure over the wetted area of each element. The resulting loads are distributed between the two nodes that bound each element and expressed as loads per unit length. The cross-sectional area of the tapered cylinders is equal to the member cross-sectional area at each node. For the blades, loads are applied at a user-specified center of buoyancy, which allows for offsets from the aerodynamic center in the directions normal and tangential to the chord. For the tower, loads are applied at the centerline. When applicable, end effects are accounted for by calculating the fluid pressure on the exposed axial face of the element.

**Hub and Nacelle**

The hub and nacelle are treated as separate components. The buoyant force is determined by the volume of either the hub or nacelle and applied at its user-specified center of buoyancy. The hub center of buoyancy is defined in local coordinates relative to the center of the hub, and the nacelle center of buoyancy is defined in local coordinates relative to a nacelle reference position that is aligned horizontally with the tower centerline and vertically with the center of the hub. Corrections are made to account for the joints between the hub and blades and the nacelle and tower, as the joint locations are not exposed to fluid pressure. No correction will be made for the joint between the hub and nacelle, and this will be mentioned in the documentation as a local limitation.

**Coordinate Systems**

The buoyant force acting on an element depends on its instantaneous orientation and depth. The orientation and depth are determined by the positions of the nodes bounding the element (i.e., nodes and ). Blade nodes are numbered in increasing order from root to tip. For each element , the node closer to the blade root is node , and the node closer to the blade tip is node . Tower nodes are numbered in increasing order from bottom to top. For each element , the node closer to the tower bottom is node , and the node closer to the tower top is node . Hub loads are placed at a single node at the hub center and nacelle loads are placed at a single node at the nacelle reference point.

Orientation

Element orientation is defined relative to the global coordinate system by the heading () and inclination () angles. The heading angle of an element gives its rotation about the global axis relative to the positive global axis. The inclination angle of an element gives its tilt relative to the positive global axis. Elements are assumed to extend from the center of buoyancy of node to the center of buoyancy of node .

, , and are the instantaneous coordinates of the center of buoyancy of node in the global coordinate system

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Depth

For land-based wind turbines, at ground level. For offshore wind turbines, at the mean sea level (MSL), with positive pointing upwards. For fixed MHK turbines, we will define at the seabed, with positive pointing upwards. This will avoid potential complications with mesh definitions resulting from negative coordinates and avoid limitations in InflowWind that restrict the velocity profile to node positions greater than zero.

**INITIALIZE**

The following changes will be made to the initialization routines to add and validate inputs, temporarily redefine the coordinate system for buoyancy calculations, add hub and nacelle point meshes, calculate parameters, and define additional outputs.

**Inputs**

* Add an input switch “MHK” to the OpenFAST driver input file and the AeroDyn driver input file (0 = not an MHK turbine, 1 = fixed MHK turbine, 2 = floating MHK turbine)
* Add MHK turbine type options “Type\_MHK\_Fixed” and “Type\_MHK\_Floating” based on the value of “MHK” to FAST\_Subs to ensure outputs written to the summary file are correct
* Add an input flag “Buoyancy” to the AeroDyn primary input file to turn on the buoyancy calculation
* Add an input variable “BlCb” (, blade buoyancy coefficient) to the AeroDyn blade input file, defined at each node as the cross-sectional area of the blade divided by the area of a circle with diameter equal to the chord length
* Add an input variable “TwrCb” (, tower buoyancy coefficient) to the AeroDyn primary input file, defined at each node as the cross-sectional area of the tower divided by the area of a circle with diameter equal to the characteristic length of the tower cross section (i.e., the “TwrDiam” input variable defined in the AeroDyn primary input file)
* Add input variables “BlCenBn” and “BlCenBt” (, , blade center of buoyancy) to the AeroDyn blade input file, defined at each node as offsets from the aerodynamic center in the directions normal (positive pointing away from the cambered side of the airfoil) and tangential (positive pointing away from the leading edge) to the chord
* Add an input parameter “VolHub” () to the AeroDyn primary input file to specify the volume of the hub
* Add an input parameter “VolNac” () to the AeroDyn primary input file to specify the volume of the nacelle
* Add an input parameter “HubCenBx” (, hub center of buoyancy) to the AeroDyn primary input file, defined as the offset from the center of the hub in the local hub coordinate system; offsets in the and directions are assumed to be zero
* Add input parameters “NacCenBx”, “NacCenBy”, and “NacCenBz” (, , , nacelle center of buoyancy) to the AeroDyn primary input file, defined as offsets from the nacelle reference position (a single point aligned horizontally with the tower centerline and vertically with the center of the hub) in the local nacelle coordinate system
* Add environmental variables currently defined in module primary input files to driver input files. DEFAULT options are added for these variables to use what is specified in the driver; otherwise, they are overwritten with the module-level values specified. Environmental variables are left in module primary input files for legacy compatibility with external users.
  + Add “Gravity” to the OpenFAST driver input file, remove from the ElastoDyn primary input file
  + Add “KinVisc” to the OpenFAST and AeroDyn driver input files, leave in the AeroDyn primary input file
  + Add “SpdSound” to the OpenFAST and AeroDyn driver input files, leave in the AeroDyn primary input file
  + Add “Patm” to the OpenFAST and AeroDyn driver input files, leave in the AeroDyn primary input file
  + Add “Pvap” to the OpenFAST and AeroDyn driver input files, leave in the AeroDyn primary input file
  + Add “AirDens” to the OpenFAST driver input file, leave in the AeroDyn primary input file
  + Add “FluidDens” to the AeroDyn driver input file
    - If running AeroDyn driver, FluidDens is passed as AirDens
  + Add “WtrDens” to the OpenFAST and HydroDyn driver input files, leave in the HydroDyn primary input file
    - If running OpenFAST driver and MHK = 1, WtrDens is passed as AirDens
  + Add “WtrDpth” to the OpenFAST, AeroDyn, and HydroDyn driver input files, leave in the HydroDyn primary input file
  + And “MSL2SWL” to the OpenFAST and HydroDyn driver input files, leave in the HydroDyn primary input file
    - If running AeroDyn driver, MSL2SWL is not accounted for
* Remove “FluidDepth” from the AeroDyn primary input file and complete the cavitation check based on the value of “WtrDpth”

**Validation**

* Check that “MHK” is set to 0, 1, or 2
* Add an error stating that functionality to model floating MHK turbines has not been added yet if a value of 2 for “MHK” is detected
* Check that AeroDyn14 is not selected when “MHK” is set to 1 or 2
* Check that “CavitCheck”, “AddedMass”, and “Buoyancy” are set to FALSE if “MHK” is set to 0
* Check that “WtrDpth” is greater than or equal to zero
* Check that “BlCb” is greater than or equal to zero if “Buoyancy” is set to TRUE
* Check that “TwrCb” is greater than or equal to zero if “Buoyancy” is set to TRUE and “NumTwrNds” is greater than zero
* Check that “VolHub” is greater than or equal to zero if “Buoyancy” is set to TRUE
* Check that “VolNac” is greater than or equal to zero if “Buoyancy” is set to TRUE
* Check that the AeroAcoustics module is not selected if “MHK” is set to 1 or 2
* Check that all analysis nodes remain within the fluid depth determined by “WtrDpth” at every time step

**Coordinate Systems**

The turbine position in the global coordinate system is defined during the initialization routines, either by ElastoDyn/BeamDyn (if driving the simulation via the OpenFAST glue code) or by individual module drivers (if running in standalone mode) and passed between modules. For fixed MHK turbines, any inputs related to absolute vertical positions will be defined relative to the seabed. The turbine position will be temporarily adjusted during the buoyancy calculation to place the origin at the MSL. This adjustment will be based on the value of “WtrDpth” and is required to accurately calculate the submergence depth, which directly affects buoyancy. It will be implemented only for the purposes of the buoyancy calculation and will not affect global mesh coordinates.

**Meshes**

To calculate and pass hub and nacelle buoyant loads to other modules, several point meshes will be added, and load meshes will be mapped to ElastoDyn.

* Hub load output
  + The current hub load mesh (m%HubLoad) is used only for writing outputs. It is created as a sibling of u%HubMotion. Since a mesh can only have one sibling, y%HubLoad should be a sibling of u%HubMotion, and m%HubLoad should be a new copy of y%HubLoad.
* Nacelle motion input
* Nacelle load output

**Parameters**

The buoyancy calculation includes some variables that do not change with time (i.e., parameters). These parameters will be calculated during initialization and passed to relevant subroutines rather than recalculated at each time step. For both the blade and tower parameters, is defined at every node, whereas , , and are defined at every node except the blade tip and tower top.

Blade Parameters

is the radius of the circular cross-sectional area at node

is the blade chord at node

is the blade buoyancy coefficient at node

is the length of the element in the axial direction

, , and are the undisplaced coordinates of the center of buoyancy of node in the global coordinate system

, , and are the undisplaced coordinates of the center of buoyancy of node in the global coordinate system

, , and are undisplaced offsets from the aerodynamic center to the center of buoyancy of node in global coordinates

, , and are the undisplaced coordinates of the aerodynamic center of node in the global coordinate system

is the transpose of the undisplaced direction cosines matrix of node , input to AeroDyn from the driver

and are offsets from the aerodynamic center to the center of buoyancy of node in local blade coordinates

indicates the taper of the element

is the axial centroid of the element, expressed as a fraction of element length

Tower Parameters

is the radius of the circular cross-sectional area at node

is the tower diameter at node (i.e., tower characteristic length)

is the tower buoyancy coefficient at node

is the length of the element in the axial direction

is the distance from the seabed to node (specified in the AeroDyn primary input file as “TwrElev”)

indicates the taper of the element

is the axial centroid of the element, expressed as a fraction of element length

**Outputs**

Buoyancy will be calculated by AeroDyn in the global coordinate system and added to the aerodynamic loads that are passed to other modules. Additionally, the following user-selectable outputs will be added.

* Lumped buoyant loads on the hub, in the hub coordinate system
  + HbFbx (x-component of buoyant force at hub node)
  + HbFby (y-component of buoyant force at hub node)
  + HbFbz (z-component of buoyant force at hub node)
  + HbMbx (x-component of buoyant moment at hub node)
  + HbMby (y-component of buoyant moment at hub node)
  + HbMbz (z-component of buoyant moment at hub node)
* Lumped buoyant loads on the nacelle, in the nacelle coordinate system
  + NcFbx (x-component of buoyant force at nacelle node)
  + NcFby (y-component of buoyant force at nacelle node)
  + NcFbz (z-component of buoyant force at nacelle node)
  + NcMbx (x-component of buoyant moment at nacelle node)
  + NcMby (y-component of buoyant moment at nacelle node)
  + NcMbz (z-component of buoyant moment at nacelle node)
* Buoyant loads per unit length at each tower node, in the tower coordinate system
  + TwN#Fbx (x-component of buoyant force per unit length at tower node)
  + TwN#Fby (y-component of buoyant force per unit length at tower node)
  + TwN#Fbz (z-component of buoyant force per unit length at tower node)
  + TwN#Mbx (x-component of buoyant moment per unit length at tower node)
  + TwN#Mby (y-component of buoyant moment per unit length at tower node)
  + TwN#Mbz (z-component of buoyant moment per unit length at tower node)
* Buoyant loads per unit length at each blade node, in the blade coordinate system
  + B#N#Fbn (buoyant force normal to chord per unit length at blade node)
  + B#N#Fbt (buoyant force tangential to chord per unit length at blade node)
  + B#N#Fbs (buoyant spanwise force per unit length at blade node)
  + B#N#Mbn (buoyant moment normal to chord per unit length at blade node)
  + B#N#Mbt (buoyant moment tangential to chord per unit length at blade node)
  + B#N#Mbs (buoyant spanwise moment per unit length at blade node)
* Total of aerodynamic and buoyant loads integrated over the rotor, in the hub coordinate system; these outputs replace RtAero\*
  + RtFluidFxh (total rotor aerodynamic and buoyant force in x direction)
  + RtFluidFyh (total rotor aerodynamic and buoyant force in y direction)
  + RtFluidFzh (total rotor aerodynamic and buoyant force in z direction)
  + RtFluidMxh (total rotor aerodynamic and buoyant moment in x direction)
  + RtFluidMyh (total rotor aerodynamic and buoyant moment in y direction)
  + RtFluidMzh (total rotor aerodynamic and buoyant moment in z direction)

**CALCULATE OUTPUT**

The following section details the buoyancy calculation for the blades, tower, hub, and nacelle. Interior and end elements are considered separately. Forces and moments will be calculated inside the AD\_CalcOutput subroutine after aerodynamic calculations have been completed. Buoyant loads will then be added to the aerodynamic loads before they are passed to other modules.

At each time step, before completing subsequent calculations, the following steps will be completed:

* Node positions will be checked to ensure that no elements cross the free surface or go beneath the seabed (i.e., global coordinates are always less than “WtrDpth+MSL2SWL” and greater than zero). This check will be completed for all members (i.e., blades, hub, nacelle, and tower).
* The global coordinates of nodes and will be adjusted by “WtrDpth” and “MSL2SWL” (if driven by OpenFAST).

, , and are the instantaneous coordinates of the aerodynamic center of node in the global coordinate system

, , and are the instantaneous coordinates of the aerodynamic center of node in the global coordinate system

**Blades**

* Members are modeled as tapered cylinders broken up into elements
* Each element is bounded by nodes and , numbered from root to tip

Tip

Root

4

3

2

1

Elements

Nodes

5 (N)

4

3

2

1

* Elements do not need to be a uniform length, as there is no restriction on the uniformity of node spacing for the blades
* Neglect marine growth

Interior elements

* Centers of buoyancy of nodes and are calculated in global coordinates
* Heading and inclination angles are calculated
* Hydrostatic fluid pressure is integrated over the wetted surface and expressed as an axial force, transverse force, and moment at node
* Forces and moments are transformed into global coordinates
* Forces and moments are distributed between nodes and
* Moments resulting from moving the buoyant force at each node from the center of buoyancy to the aerodynamic center are calculated and added to existing moments
* Buoyant loads are expressed per unit length to be compatible with aerodynamic loads
* Buoyant loads are added to aerodynamic loads

1. Calculate the center of buoyancy of nodes and in global coordinates

, , and are offsets from the aerodynamic center to the center of buoyancy of node in global coordinates

is the transpose of the instantaneous direction cosines matrix of node , input to AeroDyn from the driver

1. Calculate the heading and inclination angles for element using the equations for and given above
2. Calculate the axial force (), transverse force (), and moment () acting at node from the hydrostatic fluid pressure on the wetted surface of a tapered cylindrical element

is the fluid density

is the acceleration of gravity

1. Adjust to avoid double counting the moment caused by distributing the tangential force between nodes and
2. Convert loads computed in the local coordinate system of each element into the global coordinate system, yielding the buoyancy
3. Distribute between nodes and
4. Calculate moments caused by moving from the center of buoyancy to the aerodynamic center at nodes and () and add to existing moments (i.e., )

is the vector from the aerodynamic center to the center of buoyancy of node

1. Express at nodes and as forces and moments per unit length to be consistent with aerodynamic loads

Forces and moments at all interior nodes will be the weighted average of per-unit-length force and moment contributions from the two elements on either side of the node, with weights based on element length.

1. Add to the aerodynamic loads at node and to the aerodynamic loads at node

End elements

* Buoyant loads on end elements are calculated as for interior elements, with the addition of the fluid pressure integrated over the exposed axial face of the element
* Applicable to the first and last elements (blade root and tip)
* Buoyant forces on each blade root are calculated as if the root was exposed to fluid pressure, and these forces are added to the hub buoyant forces (equivalent to subtracting the opposite of the blade root forces from the hub forces)
* Buoyant forces on the blade tip are calculated and added to existing forces at the end node

1. Calculate the buoyancy on nodes and according to steps 1-6 for blade interior elements
2. Calculate the buoyant force acting on the axial face of the blade in global coordinates ( or )

For the blade root,

For the blade tip,

1. If considering the root element, save the values of ] and for later use. If considering the tip element, add to the existing buoyant loads at the tip node.
2. Move loads from the center of buoyancy to the aerodynamic center, express as forces and moments per unit length, and add to existing aerodynamic loads according to steps 7-9 for blade interior elements

Forces and moments at the blade tip node will be the sum of per-unit-length force and moment contributions from the element itself and the axial face.

**Tower**

* Tower buoyant loads are calculated if “Buoyancy” is set to TRUE and tower nodes are defined, regardless of the value of other tower flags
* Buoyancy on the tower is calculated similarly to buoyancy on the blades
* Nodes are numbered from tower bottom to tower top
* No adjustment is made for offsets between the center of buoyancy and tower centerline
* The tower is assumed to be embedded into the seabed so that no end effects at the tower base are needed

Interior elements

1. Calculate the heading and inclination angles for element using the equations for and given above. Note that and for tower nodes.
2. Calculate the axial force (), tangential force (), and moment () acting at node from the hydrostatic fluid pressure on the wetted surfaces of a tapered cylindrical element
3. Complete steps 4-6 and 8-9 for blade interior elements

End elements

* Applicable only to the last element (tower top)
* Buoyant forces on the tower top are calculated as if the tower top was exposed to fluid pressure, and these forces are added to the nacelle buoyant forces (equivalent to subtracting the opposite of the tower top forces from the nacelle forces)

1. Calculate the buoyancy on nodes and according to steps 1-2 for tower interior elements
2. Complete steps 4-6 for blade interior elements
3. Calculate the buoyant force acting on the axial face of the tower top in global coordinates ()
4. Save the values of ] and for later use
5. Complete steps 8-9 for blade interior elements; the loads on the axial face of the tower top are added to the nacelle and do not contribute to the loads on the last tower element

**Hub**

* Buoyant force is determined by the volume of the hub and applied in the positive global direction at its center
* End effects at blade joints are accounted for by adding the buoyant force that would act on the axial face of each blade root if the root were exposed to fluid pressure

1. Calculate the buoyant force acting on the hub ()

is the volume of the hub

1. Calculate moments resulting from moving the buoyant force from the center of buoyancy to the center of the hub ()

is the vector from the center of the hub to the hub center of buoyancy

is the transpose of the instantaneous direction cosines matrix of the hub, input to AeroDyn from the driver

is the offset from the center of the hub to the hub center of buoyancy in local hub coordinates

1. Calculate moments resulting from moving the blade root correction force from the blade root location to the center of the hub for each blade ()

is the vector from the center of the hub to the center of buoyancy of the root node

is the buoyant force on the axial face of the blade root, calculated previously and saved

, , and are the global coordinates of the center of the hub

, , and are the global coordinates of the center of buoyancy of the blade root, calculated previously as ] and saved

1. Combine all forces and moments at the hub center

**Nacelle**

* Buoyant force is determined by the volume of the nacelle and applied in the positive global direction at the nacelle reference position
* End effects at the tower joint are accounted for by adding the buoyant force that would act on the axial face of the tower top if it were exposed to fluid pressure

1. Calculate the buoyant force acting on the nacelle ()

is the volume of the nacelle

1. Calculate moments resulting from moving the buoyant force from the center of buoyancy to the nacelle reference position ()

is the vector from the nacelle reference position to the nacelle center of buoyancy

is the transpose of the instantaneous direction cosines matrix of the nacelle, input to AeroDyn from the driver

, , and are offsets from the nacelle reference position to the nacelle center of buoyancy in local nacelle coordinates

1. Calculate moments resulting from moving the tower top correction force from the tower top location to the nacelle reference position ()

is the vector from the nacelle reference position to the center of buoyancy of the tower top node

is the buoyant force on the axial face of the tower top, calculated previously and saved

, , and are the global coordinates of the nacelle reference position

, , and are the global coordinates of the center of buoyancy of the tower top, calculated previously as ] and saved

1. Combine all forces and moments at the nacelle reference position

**UPDATE STATES/END**

Update states and end routines should be unaffected by these changes.