Drivetrain modeling in OpenFAST

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21st March 2024

1 Introduction

This document presents a method for including bending degrees of freedom of a drivetrain in OpenFAST and obtain main bearing loads.

1.1 ElastoDyn and SubDyn

To model the drivetrain in OpenFAST, we divide the RNA in two, split at the shaft. In ElastoDyn, everything that is rotating, and rotational inertia, is included: rotor, hub mass and inertia, generator torsional inertia and drivetrain torsional stiffness and damping. SubDyn and ElastoDyn are connected at the shaft, and in SubDyn nothing rotates with the rotor (SubDyn doesn't allow for large rotations). The shaft, bearings, gearbox, bedplate and generator is included in SubDyn.

1.1.1 Interface

Information exchange between the two modules occurs through "nodes" called the platform reference point and interface joint, for ElastoDyn and SubDyn, respectively. The reader is referred to the SubDyn documentation [1] for more information about these OpenFAST modules, but one can note that these points are not located in the same position. ElastoDyn only allows for the platform reference point to be located along at (X,Y)=(0,0) in the global coordinate system. SubDyn receives information about motions and velocities of the platform reference point and establishes a fully linear rigid link internally between the interface joint and the platform reference point (which is refered to as TP (transition piece) reference point in SubDyn). The interface joint in the SubDyn drivetrain model should be located at the shaft tip.

1.2 Modeling in ElastoDyn

1.2.1 Tower

When modeling the tower and drivetrain in SubDyn, the tower of ElastoDyn is only a dummy tower linked to the ElastoDyn shaft. It should be light and short.

```
---------------------- DISTRIBUTED TOWER PROPERTIES ----------------------------
  HtFract   TMassDen   TwFAStif   TwSSStif   TwGJStff   TwEAStff   TwFAIner   TwSSIner   TwFAcgOf   TwSScgOf
   (-)      (kg/m)     (Nm^2)     (Nm^2)     (Nm^2)     (N)        (kg m)     (kg m)     (m)        (m)
   0        1E-6       1E+12      1E+12      1E+12      1E+12      1E+05      1E+05      0          0
   1        1E-6       1E+12      1E+12      1E+12      1E+12      1E+05      1E+05      0          0
```

Figure 1: Light dummy tower in ElastoDyn

This means setting *TowerBsHt* to, say, 0.01 m below the *TowerHt*. The *Twr2Shft*-parameter is of similar length (0.01 m), to keep the platform reference point *PtfmRefzt* as close to the SubDyn Interface joint as possible.

This is exemplified here by a turbine with tower height 98 m, and a vertical distance from tower top to (the elongated) shaft of 2 m:

- *Twr2Shft* = 0.01
- *TowerHt* = 99.99
- *TowerBsHt* = 99.98
- *PtfmRefzt* = 99.98

The ElastoDyn tower property file should have a low mass and a high stiffness, see e.g. Figure 1.

1.2.2 DOFs

The platform degrees of freedom need to be enabled (also when considering a bottom-fixed turbine), because these are now located at the bottom of the dummy tower, and are effectively the degrees of freedom of the shaft tip:

- *PtfmSgDOF* = True
- *PtfmSwDOF* = True
- *PtfmHvDOF* = True
- *PtfmRDOF* = True
- *PtfmPDOF* = True
- *PtfmYDOF* = True

On the other hand, the tower DOFs should be disabled, because it is now just a dummy tower. It is only there because ElastoDyn is built so that it needs tower input.

- *TwFADOF1* = True
- *TwFADOF2* = True
- *TwSSDOF1* = True
- *TwSSDOF2* = True

Finally, we want to include the drivetrain torsional flexibility on the rotating ElastoDyn-side of the model. Hence, we also enable *DrTrDOF*.

1.2.3 Mass and inertia

The hub mass and inerta and the generator inertia should be kept as in a traditional OpenFAST-model. However, nacelle mass and yaw inertia, yaw bearing mass, and platform mass and inertia should all be set to zero, otherwise there will be masses hanging at the shaft tip in SubDyn. An exception is the roll inertia (*PtfmRIner*). Finally, ElastoDyn needs a counteracting roll-inertia to avoid unbalanced rotor inertia. A dummy roll-inertia should therefore be assigned at the platform reference point.

1.3 Modeling in SubDyn

1.3.1 Shaft

The shaft is modeled using a flexible beam in SubDyn. The joint closest to the rotor should be an interface joint. The other end of the shaft is then rigidly connected to the gearbox (gearbox modeled as a point mass and inertia).

Note that the shaft should be stiff in torsion, as torsional flexbility is contained on the rotating, ElastoDyn-side. To obtain a shaft that is stiff in torsion, the shaft torsional stiffness can tuned to be a couple of orders larger than the drivetrain torsional spring constant in ElastoDyn ($K_{\alpha\alpha_{ED}}$). G is calculated as

$$G = \frac{100 K_{\alpha\alpha_{ED}}}{I_x}. \tag{1}$$

Note that when modeling the shaft as a beam, it intrinsically has inertia about the torsional degree of freedom. This inertia is already accounted for in the rotating part of the model, and is therefore included twice. However, the shaft torsional inertia is typically many orders of magnitude lower than the rotor inertia and generator inertia (when cast to the low speed side), both of which are included in the rotating part of the model. Hence, the shaft torsional inertia is expected to have minimal impact on results.

An example of how to derive shaft material properties and geometries from a finite element model of a shaft is provided in Appendix A.

1.3.2 Main bearings

Along the shaft, one can define springs connected to the shaft nodes, representing the main bearings. Typically, the bearings will have stiffness matrices without coupling elements, and with zero torsional stiffness. At least one bearings should have axial stiffness, and both bearings (if two) typically have stiffness in the radial degrees of freedom (F_y, F_z). Some bearings also exhibit bending stiffness. These springs have no mass or length. They should be connected to a bedplate through rigid links, or, if operating with a rigid bedplate, they can be connected directly to the tower.

1.3.3 Torque arms

The gearbox is typically supported by torque arms (gearbox supports), designed to take up torque from accelerations in the shaft. To allow for this, they are placed a certain distance from the gearbox on each (lateral) side of the gearbox. The gearbox mass and the extension of the shaft is connected to the torque arm springs through rigid links, which are further connected to the bedplate (or tower, if rigid bedplate) by more rigid links.

1.3.4 Gearbox

At the downstream end of the shaft, a rigid link connects the shaft and the gearbox, which is modeled as a point mass and inertia. This gearbox is further connected to rigid links extending laterally to the torque arms

1.3.5 Generator

The generator coupling is normally assumed to have a soft coupling to the gearbox, so that it doesn't take up any loads other than the torque (which is handled in ElastoDyn). Hence, the generator can be modeled by a separate point mass and inertia, connected by rigid links to the bedplate (or tower if bedplate is rigid). Note that generator torsional inertia should be included on the ElastoDyn side, not in SubDyn.

1.3.6 Number of Craig-Bampton modes

The number of Craig-Bampton modes necessary to accurately capture shaft and bearing loads should be investigated by means of sensitivity analysis. For the 10-MW DTU reference turbine, internal modes up to a frequency of 18 Hz were required to properly capture axial loads in the shaft. Compatibility between shaft loads in ElastoDyn and shaft loads in SubDyn should be checked in a convergence test.

1.4 Limitations

1.4.1 Aerodynamic loads

Aerodynamic loads on the tower and tower shadow is not yet supported for towers modeled in SubDyn.

1.4.2 Nacelle yaw

Nacelle yaw is not possible with the current setup.

References

[1] NREL. SubDyn User Guide and Theory Manual. `https://openfast.readthedocs.io/en/main/source/user/subdyn/modeling.html`. Accessed on: 2024-03-21.

A Shaft dimension derivations

An example of how to obtain shaft properties from a shaft modeled in finite element code is given here. By applying static forces and moments to the shaft tip, fixing the shaft in the downstream end, and extracting corresponding displacements and rotations, shaft properties can be calculated.

Equation 2 shows the stiffness matrix representative of Euler-Bernoulli beams.

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} \frac{EA_x}{L} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{12EI_z}{L^3} & 0 & 0 & 0 & \frac{6EI_z}{L^2} \\ 0 & 0 & \frac{12EI_y}{L^3} & 0 & -\frac{6EI_y}{L^2} & 0 \\ 0 & 0 & 0 & \frac{GI_x}{L} & 0 & 0 \\ 0 & 0 & -\frac{6EI_y}{L^2} & 0 & \frac{4EI_y}{L} & 0 \\ 0 & \frac{6EI_z}{L^2} & 0 & 0 & 0 & \frac{4EI_z}{L} \end{bmatrix} \begin{bmatrix} u_x \\ u_y \\ u_z \\ \theta_x \\ \theta_y \\ \theta_z \end{bmatrix} \tag{2}$$

An equation for the length of an axi-symmetric shaft is found by dividing Equation 3 by Equation 4.

$$F_y = \frac{12EI}{L^3}u_y + \frac{6EI}{L^2}\phi_z \tag{3}$$

$$M_z = \frac{6EI}{L^2}u_y + \frac{4EI}{L}\phi_z \tag{4}$$

The length of the shaft can then be found by solving Equation 5.

$$2F_y\phi_z L^2 + 3(F_y u_y - M_z\phi_z)L - 6M_z u_y = 0 \tag{5}$$

The expressions for the inner and outer diameter are derived in Appendix A, and summarized in Equation 6.

$$D_i < \sqrt{\frac{1}{2}\frac{8F_yL^2u_x}{F_x(6u_y + 3L\phi_z)}} < D_o < \sqrt{\frac{8F_yL^2u_x}{F_x(6u_y + 3L\phi_z)}} \tag{6}$$

Choosing values for D_o and D_i according to these limitations, E is then found as

$$E = \frac{F_xL}{Au_x}. \tag{7}$$

Having found L from the Equation 5, E, D_o, D_i remain unknowns.

From Equation 3 above we can find EI as

$$EI = \frac{F_y}{\frac{12}{L^3}u_y + \frac{6}{L^2}\phi_z}$$

or

$$E(D_o^4 - D_i^4) = \frac{64}{\pi}\frac{F_y}{\frac{12}{L^3}u_y + \frac{6}{L^2}\phi_z}.$$

Looking at the axial stiffness,

$$\begin{aligned} F_x &= \frac{EA}{L}u_x \\ E &= \frac{F_x L}{A u_x}, \end{aligned}$$

and applying the expression for E in the equation above, we get

$$\begin{aligned} \frac{F_x L}{A u_x}(D_o^4 - D_i^4)\frac{\pi}{64} &= \frac{F_y}{\frac{12}{L^3}u_y + \frac{6}{L^2}\phi_z} \\ \frac{\frac{\pi}{64}(D_o^4 - D_i^4)}{\frac{\pi}{4}(D_o^2 - D_i^2)} &= \frac{u_x}{F_x L}\frac{F_y}{\frac{12}{L^3}u_y + \frac{6}{L^2}\phi_z} \\ D_o^2 + D_i^2 &= 16\frac{u_x}{F_x}\frac{F_y}{\frac{12}{L^2}u_y + \frac{6}{L}\phi_z} \\ D_o^2 + D_i^2 &= \frac{8F_y L^2 u_x}{F_x(6u_y + 3L\phi_z)} \\ D_o^2 + D_i^2 &= a \\ D_o^2 &= a - D_i^2. \end{aligned}$$

Utilizing the fact that $D_i < D_o$ and denoting the right-hand side of the above equation as a we find an upper limit for the inner diameter.

$$\begin{aligned} D_i &< D_o \\ D_i^2 &< D_o^2 \\ D_i^2 &< a - D_i^2 \\ 2D_i^2 &< a \\ D_i &< \sqrt{\frac{a}{2}} \end{aligned}$$

Requiring a thickness greater than zero, we further obtain an upper diameter for the outer diameter,

$$D_o < \sqrt{a}.$$

From here, D_o and D_i can be chosen within the obtained limitations. Then, E is found as

$$E = \frac{F_x L}{A u_x}$$