The Influence of Synthetic Mooring Line Stiffness Model Type on Global Floating Offshore Wind Turbine Performance

W M West¹, A J Goupee¹, A M Viselli¹ and H J Dagher¹
¹Advanced Structures and Composites Center, Orono, ME, United States

Abstract. Floating offshore wind turbines (FOWTs) over the past decade have been targeted as a solution to reducing dependence on fossil fuel. At this point the hulls of FOWTs have been a huge point of emphasis for the research community. FOWT mooring systems, however, have recently started to garner more attention. One solution that has gained traction to reduce cost is mooring the turbine with a synthetic mooring system as opposed to the traditional chain catenary system. Currently there is guidance provided for designing synthetic mooring systems, but it is more geared to the needs of the offshore oil and gas industry, and often leads to conservative designs. This work investigates the stiffness models recommended by the design guides and their influence on FOWT global response.

1. Introduction
FOWTs have the ability to access 70% of the U.S. offshore wind resource which is currently inaccessible for fixed-bottom foundation technology. FOWT foundation technologies are evolving rapidly, and the first commercial farms in the U.S. are expected in the near future. A major challenge for these farms is the mooring system. Conventional moorings consist of chain catenary systems which have a large footprint and are costly, especially when deployed in shallow water depths of less than 100 meters. One potential solution that has received attention recently is the idea of using taut synthetic lines in place of steel chain systems [1]. Currently, chain catenary systems are the overwhelming choice for anchoring FOWT installations. With a chain system the platform restoring force is provided by the weight of the chain and the geometry of the system. When using synthetic lines, namely polyester and nylon, the axial elongation of these lines is used to restrict FOWT motions. Like many of the designs used in the offshore wind industry the concept of using synthetic ropes was pioneered by the offshore oil and gas industry.

There currently exists a few different design standards that dictate how to design and model synthetic fiber mooring systems. These standards include the American Bureau of Shipping’s (ABS) Guidance Notes on the Application of Fiber Rope for Offshore Mooring [2] as well as others from Det Norske Veritas [3] (DNV) and the American Petroleum Institute [4] (API). The issue with these design standards is that they were written with the intent of guiding the design of mooring systems for the offshore oil and gas industry, which have installations in much deeper water. As such, these design guides do not provide the details necessary to design synthetic station-keeping systems for FOWTs.
A primary challenge using current standards for FOWT station keeping design are the modelling methods suggested for synthetic mooring systems. Synthetic fiber ropes are extremely nonlinear materials with responses that are complicated to predict. Some of the physical phenomenon which occur in synthetic ropes include nonlinear force-elongation curves, creep and hysteresis responses [1]. As a result, the design standards often recommend using very simplified stiffness models for the lines but leave the option open for more advanced stiffness models to be used.

2. Synthetic Fiber Design Standards
There currently exist a few different design standards that dictate how to design and model synthetic fiber mooring systems. The issue with these design standards is that they were written with the intent of guiding the design of mooring systems for the offshore oil and gas industry for vessels that were to be deployed in deep waters (> 1000 meters). For these large depths the weight of chain and steel cable mooring systems were becoming prohibitively heavy, and synthetics were explored as an alternative for their much lower weight. The design requirements for the offshore oil and gas industry and the floating offshore wind industry are two very different things and as a result the ABS, DNV and API do not provide the guidance necessary to design synthetic station-keeping systems for FOWTs.

The first issue within the guides concerns the materials covered. When synthetic mooring line technology was being explored by the offshore oil and gas industry the fibers that were of interest were mainly polyester, Dyneema and aramid fibers. The first ABS Guidance Notes on the Application of Fiber Rope for Offshore Mooring was originally written in 1999 [5] when the only industry looking into the use of synthetic moorings was the offshore oil and gas industry. Naturally these design standards tend to mirror the needs and cover the materials that are of interest to that industry.

Unfortunately, these fibers are generally too stiff to be useful in station-keeping systems for FOWTs. The high modulus fibers developed for the oil and gas industry were designed to have strength and stiffness properties similar to steel cable but have a specific gravity that falls close to one in order
to decrease the weight of the mooring system. For FOWTs in shallow to modest water depths (45 meters – 80 meters) these materials tend to be far too stiff, and other options will need to be explored.

While these stiff materials are ideal for deep water applications, FOWT deployed in shallow water have much different needs. Using stiff ropes in these shallow water applications will lead to a few issues. First stiffer ropes will tend to attract more loads from the motion of the FOWT caused by the wave loading, and second stiff ropes can change the natural periods of the platforms potentially leading to resonance issues.

Another shortfall of the design standards are the modelling methods suggested for synthetic mooring systems. Synthetic fiber ropes exhibit some extremely unique physical phenomenon such as non-linear force-elongation relationships, creep and hysteresis responses. As a result, the design standards recommend using very simplified stiffness models for the lines but leave the option open for more advanced stiffness models to be used [2].

ABS recommends that the static-dynamic model be used in their Application of Fiber Rope for Offshore Mooring guide [2]. The static dynamic model is basically a bilinear model where the lower stiffness of the model is the post-installation stiffness, and the higher stiffness of the model is the storm stiffness. These values can then be used to calculate both the maximum offsets and maximum line tensions. The other model that the ABS recommends is the upper/lower bound stiffness model [2]. For this model two different stiffnesses are chosen, and the analysis is run twice. The lower stiffness will provide information about the maximum platform offsets, and the higher stiffness model will determine the maximum tension in the line. These models are a good starting place; however, ABS leaves the option for designers to use other models as long as they reflect the behavior of synthetic ropes, produce realistic platform offsets and mooring line tensions, and account for line length changes due to phenomenon such as creep.

Another agency providing guidance on how to model synthetic moorings is DNV. In their guide Offshore Fibre Ropes (DNGL-OS-E303) [3] DNV recommends a model called the nonlinear viscoelastic model. This is a model developed by John Flory and is designed to tackle all of the responses unique to synthetic fiber ropes including creep and hysteresis.

The last agency providing guidance on synthetic mooring stiffness models is API. In their guide Design and Analysis of Stationkeeping Systems for Floating Structures (API RP 2SK) [4]. API recommends three different mooring stiffness models. The first is the upper/lower bound stiffness model. This model is identical to the model proposed by ABS. The next model is the nonlinear load-elongation model [3]. In this method the rope’s force-elongation properties are modelled non-linearly in one of two ways. Either an analytical expression can be determined, or alternatively a lookup table can be constructed. The last way that the entire system can be modelled is using a frequency method [3]. This method is effective because the stiffness of synthetic mooring lines can correlate with the forcing frequency. In this method three different stiffness values are chosen for calculating the mean, low frequency, and wave frequency responses. A brief summary of the design guide-recommended stiffness models is shown in Table 1.
Table 1. Summary of Recommended Stiffness Models

| Model Name                          | Model Description                                                                                                                                                                                                 | Code Agency Allowing Use |
|-------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|
| Static Dynamic Model                | The static stiffness is softer and used up to a mean loading. After the mean loading a stiffer dynamic stiffness is used.                                                                                           | ABS [2]                  |
| Upper-Lower Bound Model             | Two stiffnesses are chosen. The upper bound is the largest stiffness expected and the lower bound is the smallest stiffness expected. The analysis is run for each case and the maximum tensions and offsets are found. The actual system will lie somewhere between the upper and lower bound stiffnesses. | ABS [2], API [4]         |
| Nonlinear Viscoelastic              | The lines are modelled as different viscoelastic setups such as the Kelvin Model and the Generalized Maxwell Model. These models are made up of springs and dampers in parallel and series and give realistic responses of the lines. | DNV [3]                  |
| Nonlinear Load Elongation Model     | Load-Elongation properties are modelled by expressing the load-elongation relationship analytically or by using lookup tables.                                                                                             | API [4]                  |
| Separate Decoupled Frequency Responses | The response due to the mean environmental loading, low frequency wave, current and wind loads, and high frequency wind loads are calculated separately, and the responses are added together.                          | API [4]                  |

The models presented have a few shortcomings. The first, and probably largest problem which must be overcome is the fact that the guides do not provide any suggestions for choosing the stiffness values required by the various stiffness models. The next issue with these stiffness models is that they do not always accurately reflect the material properties of the lines. Many of these stiffness models are greatly simplified which can lead to uncertainty, and over-conservative designs. In the floating offshore wind industry, an over-conservative design can potentially make an otherwise potentially promising FOWT concept economically infeasible.

In addition, the materials classed as appropriate by the design agencies are not necessarily applicable to the floating offshore wind industry. Many of the materials that were suitable for use in the offshore oil and gas industry, and the extreme depths the industry is interested in, are not practical for the offshore wind industry [1]. In order for synthetic moorings for offshore wind to become a reality for commercial turbines other materials, such as nylon which are more compliant than typical synthetics used in offshore engineering applications, would need approval. In addition, the sophistication of the stiffness models recommended for design should be sufficiently high as to remove the conservatism of FOWT station-keeping designs, and make synthetic lines a profitable, and feasible option.

3. FAST Upgrades and Methodology
In order to fully understand the fully-coupled dynamic response of a FOWT moored with a synthetic mooring system it is necessary to implement the stiffness models discussed in Table 1 into an appropriate multi-physics simulation. Fortunately, FAST Version 8 is a comprehensive open-source software for
modelling the coupled dynamic response of FOWTs subject to wind and wave loads that is designed to be interfaced with other modules, and easily modified and expanded to fit researchers’ needs [6]. The architecture of how FAST communicates with different modules is illustrated in Figure 2. The key elements of FAST are AeroDyn, ElastoDyn, HydroDyn and ServoDyn. ElastoDyn handles the dynamics of the wind turbine as well as tower and platform responses, as well as being the driver that communicates with all other modules. HydroDyn and AeroDyn calculate the hydrodynamic and aerodynamic loading on the FOWT and ServoDyn can be used to simulate the FOWT’s control system. FAST also has many options for modeling the mooring system. One of these modules, MoorDyn, employs a lumped mass mooring model (LMM). With this model the line is discretized into a number of lumped masses that are connected with springs and dampers. With the LMM fluid loading and inertia of the line can be considered [7]. This module will be modified to handle some of the synthetic stiffness models recommended by ABS, DNV, and API and afterward, fully-coupled simulations will be run to determine the influence synthetic mooring line stiffness models have on the global response of a FOWT.

![Figure 2. FAST system architecture showing how different components and modules within FAST interface with one another [6].](image)

### 3.1. MoorDyn Modifications

To modify the stiffness models within MoorDyn, Microsoft Visual Studio with the Intel Fortran Compiler was used. This allowed the source code for MoorDyn to be opened, modified and compiled into a new executable file. Aspects of the implementation such as the discretization, hydrodynamic loading on the lines, and solution algorithms were not altered. Other aspects of the line physics such as fluid loading and seabed interactions were also left unchanged. The only thing that was modified for this work was the treatment of the line properties.

MoorDyn was modified to handle a nonlinear stiffness model. The original MoorDyn input file allowed for only a linear stiffness of the mooring line material to be entered. Commercial software such as Ansys AQWA can handle higher order stiffness relationships. The way it handles this is by taking the coefficients of a polynomial which represents the variation in stiffness with deformation for the line. The MoorDyn input file was setup to take stiffness data in the same way that Ansys AQWA input file was which allowed manufacturer stiffness-elongation data to be fit with a polynomial and then input into MoorDyn. For simplicity the stiffness of the line in MoorDyn was modified to take the y-intercept of the stiffness curve, and the slope (i.e., a quadratic force-elongation relationship).

The original MoorDyn tension calculation occurs in the portion of the code that is responsible for calculating the forces on each discretized mooring line mass. The manner in which the standard
MoorDyn code calculates the line tension is to construct an axial strain ‘vector’ in the direction that the line segment is oriented. This axial strain ‘vector’ is then multiplied by the stiffness of the line effectively mapping the axial strain to a force (tension) vector. Mathematically this is represented in Equations (1) and (2).

\[ T = EA\varepsilon \]  
\[ \varepsilon = \left( \frac{1}{l} - \frac{1}{|r_{i+1} - r_i|} \right) (r_{i+1} - r_i) \]  

Where:  
- \( T \) is the tension vector in the line segment  
- \( \varepsilon \) is the axial strain vector in the line segment  
- \( l \) is the unstretched length of the line segment  
- \( r \) is the position of the lumped mass

Although this method works well for a linear relationship between line strain and tension, this implementation does not work with a higher order force-elongation relationship. An example where a different approach is needed occurs when the tension varies with respect to the axial strain quadratically. The relationship between the line extensional strain and tension in this case is given by Equation (3).

\[ T = EA\varepsilon + \frac{1}{2}k_1\varepsilon^2 \text{ for } \varepsilon \geq 0 \]  
\[ T = 0 \text{ for } \varepsilon < 0 \]  

Where:  
- \( T \) is the tension in the line segment  
- \( EA \) the line stiffness at zero strain  
- \( \varepsilon \) is the strain in the line  
- \( k_1 \) is the slope of the line stiffness

When trying to calculate the tension in the line the second-order term causes issues. In MoorDyn the axial strain is represented as a vector as shown in Equation (1). Trying to square the vector will not preserve the correct direction or magnitude needed for the calculation, so it is necessary to decompose this vector into each of its components. This is done using Equation (4).

\[ \varepsilon_i = \left( \frac{r_i - l}{l} \right) \]  

Where:  
- \( \varepsilon_i \) is the axial strain of strain in the \( e_1, e_2 \) or \( e_3 \) direction  
- \( r_i \) is the position of the lumped mass in the \( e_1, e_2 \) or \( e_3 \) direction

Once the axial strain component in each of the directions has been found, the magnitude of the strain can be determined. This strain can then be used in Equation (3) to obtain the magnitude of the tension. The last step of this process is to take the magnitude of the tension and resolve it into each of the components using Equation (5).

\[ T_i = \frac{\varepsilon_i}{\sqrt{\varepsilon_i^2}} T \]  

Where:  
- \( T_i \) is the \( e_1, e_2 \) or \( e_3 \) component of strain for computing line tension

Before FAST with the updated MoorDyn module could be used to run fully coupled FOWT simulations it was necessary to verify that it was working correctly. The simplest way to do this was to
construct mooring force-displacement plots. Although this seems like a fairly simple way to verify that the modified code was working properly, this was sufficient for the purposes of this work. This is because the other physics of this module such as the fluid and inertial loading were validated by Hall and Goupee [7]. If the tensions resulting from a static displacement in the mooring system can be properly estimated, it is assumed that the other aspects of the code involved with dynamic motion and fluid loading will continue to function properly.

Figure 3. Static line tension comparisons between AQWA and FAST to verify the tension in the line is calculated correctly

Figure 3 shows a plot of the static surge-force displacement response comparison for the University of Maine’s VolturnUS floating hull moored with a nylon rope using both the modified MoorDyn/FAST and AQWA. For this comparison the chain leader at the bottom of the mooring line was neglected for simplicity. The comparison matches very well which provides confidence that the MoorDyn code modifications are able to calculate the correct tensions resulting from axial deformation of the line.

Figure 4. University of Maine's VolturnUS Floating Hull Technology
4. Fully-coupled Platform Response for Various Stiffness Models Subjected to ABS Design Load Cases

After the modified MoorDyn code had been verified by constructing the mooring system force-displacement curves, fully-coupled simulations using the University of Maine’s VoltumUS FOWT concept with various mooring line stiffness models were run. The purpose of these simulations was to understand the influence of the choice of mooring line stiffness model on the global response of the FOWT. For these simulations 2 design load cases (DLCs) were chosen. The wave and wind environments run are shown in Table 3. These environments are representative of the major environments of interest that a FOWT could encounter without simulating all the different possibilities. First it includes an operational case at the turbine’s rated wind speed which strongly influences fatigue loading in the FOWT. Second it includes an extreme operation case which often drives ultimate load in the FOWT, and thus key design elements of these FOWT systems.

Table 2. Fully Coupled FOWT Simulation Environments [8]

| Design Load Case | Description       | Hs (m) | Tp (s) | Gamma | Mean Hub Height Wind Speed (m/s) |
|------------------|-------------------|--------|--------|--------|----------------------------------|
| DLC 1.2          | Normal Production | 1.2    | 7.3    | 1.6    | 12                               |
| DLC 1.6          | Extreme Operation | 8.5    | 12.8   | 2.75   | 12                               |

In addition to choosing the appropriate environments it was also necessary to decide what global FOWT responses were important to study. One of the major design requirements of a FOWT is to limit the nacelle accelerations. Turbine manufacturers specify a maximum nacelle acceleration which makes it an important response to accurately predict in simulations. Another important response is the line tensions as this will ultimately drive the mooring line, fairlead connection and anchor design. Other quantities of interest include tower-base bending moments and platform rigid body motions as these quantities will provide insight on the FOWT structural loads and response to environmental loads. For this part of the study nacelle fore-aft acceleration and surge response will be studied.

For these simulations the ABS recommended upper-lower bound models were used as well as the MoorDyn-implemented nonlinear stiffness model. One of the problems with the upper-lower bound models discussed in Chapter 1 is determining the upper and lower stiffness values as there is not a prescribed method provided by ABS to determine these values. This can often lead to arbitrarily selected value [2]. When designing a FOWT installation DLC 6.1 tends to be a key load case for ensuring a safe design, so the values that were chosen for this study were the stiffnesses corresponding to the minimum and maximum tensions expected from DLC 6.1 simulations. The stiffness values for the upper and lower bound stiffnesses were chosen as 8.11 × 10^7 N and 4.56 × 10^7 N respectively.

To simplify the analysis the chain leader at the seabed one would typically use for a practical FOWT mooring system was left out for the fully-coupled simulations run here. In addition, for each of these simulations the same mooring radius and unstretched line length were used. The rope data utilized corresponded to a 155mm nylon line of parallel strand construction. Simulation results are presented for ABS DLCs 1.2 and DLC 1.6 at the wind turbine’s rated wind speed. The DLC 1.2 and 1.6 simulation were run for 2400 and 4000 seconds respectively with the first 250 seconds of transients for both cases being removed as the ABS specifies. These two environments are good candidates for comparison because the turbine is operating in both instances, which provides a strong thrust force which the mooring system must resist in addition to the platform wave loading. The sea state used in DLC 1.2 is representative of more common, everyday environments that drive fatigue response, whereas the DLC 1.6 sea state is much larger and often drives ultimate loads in the FOWT. Both tension-time history and power spectral density (PSD) plots from these simulations for the surge response of the vessel, as well
as fore-aft nacelle acceleration were generated to investigate the effects of the various recommended stiffness models.

**Figure 5.** DLC 1.2 Nacelle Fore-Aft Acceleration

**Figure 6.** DLC 1.2 Platform Surge
The results in Figure 4 through Figure 7 show that the line stiffness model chosen can have a large impact on some of the responses for larger sea states. There are a few key findings from these results. First is that for larger sea states the model chosen is more important for trying to predict accurate responses. This is shown when comparing both Figure 5 and Figure 7 as well as Figure 6 and Figure 8. For each of these two examples PSD plots for the smaller DLC 1.2 environment are actually quite close.
For the larger DLC 1.6 sea states the stiffer upper bound stiffness model leads to greater nacelle accelerations and surge responses. This makes intuitive sense as one would expect stiffer lines to attract more loads to the systems and lead to greater accelerations. The stiffer mooring systems are going to lead to larger forces on the platform and thus larger accelerations. The nacelle fore-aft accelerations observed in both Figure 4 and Figure 6 illustrate this point well.

The next interesting finding involves the low frequency response for surge being shifted depending on the stiffness model used. Stiffer models lead to a higher natural frequency than more compliant stiffness models do. Surge natural frequency depends on the mooring system which depends greatly on the stiffness of the line. When checking resonance issues on the FOWT this could be problematic as the current recommended stiffness values do not agree. The simulation results presented suggest that in order to be able to accurately predict the FOWT response the rope stiffness models in large sea states that control the design stiffness models must be updated for fully-coupled simulation software.

5. References

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