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USE OF AN ELECTRO-OPTICAL-MECHANICAL MOORING CABLE FOR OCEANOGRAPHIC BUOYS: MODELING AND VALIDATION

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ABSTRACT

This paper presents results of numerical modeling of an oceanographic mooring system and makes comparisons to loads measured on a deployed test mooring near Monterey Bay, California. The numerical modeling solves the non-linear equations of motion of the cable in the time-domain. The deployed system is instrumented to monitor environmental loading and the resulting tensions in the mooring cable below the buoy and above the anchor. Comparison of the numerical results to the measured results is useful to refine the accuracy of the model, allowing its use in determining fatigue life of the system and for designing similar systems to be deployed in new locations. This study is part of a project to develop and improve mooring systems for oceanographic use that include an electro-optical-mechanical mooring cable that delivers power and data communication to a network of sea-floor instrumentation. The modeling and test results highlight the engineering challenges associated with designing these systems for long lifetimes.

INTRODUCTION

The Monterey Bay Aquarium Research Institute (MBARI) is working to develop an oceanographic buoy mooring system that provides an electrical power and high-bandwidth communication connection between the ocean surface and the seafloor in deep areas of the ocean. This system is part of the MBARI Ocean Observing System (MOOS) that is being developed in accordance with expected needs of the National Science Foundation's Ocean Observing Initiative efforts [1]. While the technology for low-bandwidth acoustic communication links to the seafloor is maturing [2, 3], these system's are limited in their bandwidth, typical performance is around 5000 bits per second, but total data throughput and service duration is limited by the lack of a power supply on the ocean floor [4]. The system being developed at MBARI is one of a handful of new systems that provide a moderate power connection, 0(100 Watts), and a very high-bandwidth data connection via mooring cables that incorporate copper wires and optical fibers in the mooring strength member. Experience with this sort of Electrical-Optical-Mechanical (EOM) cable in buoy mooring systems is limited. This paper outlines efforts at MBARI to develop new understandings of the tension loading and repetitive bending conditions such EOM cables must be tolerant of for the mooring system to have an extended service life. The overall effort includes the deployment of test systems in the eastern Pacific near Monterey Bay, development of laboratory test protocols to assist in qualifying EOM cables for this type of service, and the development of verified numerical models that accurately predict the loading on the system across a wide range of conditions.

The numerical modeling aspect of the effort is important to allow confident deployment of this system in locations with different environmental conditions than found in Monterey Bay. Furthermore, to be economically viable for scientific research, these systems need to have service lives in the three to five year range. Laboratory testing of various EOM cable designs is being performed concurrently with the test deployments. The numerical models inform this testing by providing a means of estimating

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the number and serverity of the bending and axial tension fatigue cycles the system must endure over a long-term deployment.

Because of these needs for accurate, verified numerical models of the mooring system, the test mooring installations are instrumented to measure environmental loading due to wind, waves, and currents. Additionally, the tensions in the mooring cable at the anchor and below the buoy are measured throughout the deployment. These results are transmitted in real time from the buoy via satellite. Also, additional instrumentation designed to measure accelerations in three directions is embedded at several locations along the mooring cable. These instruments log accelerations and do not report data in real-time, hence these results won't be available until the current test system in recovered in April, 2005.

This paper presents comparisons of the actual measured tensions with the numerical predictions in a variety of conditions. Because of the large amount of data measured in a wide variety of conditions during the year-long deployment, an opportunity for tuning the model for better performance exists and is discussed.

MOORING SYSTEM DESIGN OVERVIEW

The principle challenge to overcome in the implementation of a mooring system with electrical and optical conductors is related to the very low stretch tolerance of these materials. Typically, low modulus materials such as nylon and polyester are chosen for mooring lines and cables to provide a large degree of compliance to accommodate wave and tidal loading. Unfortunately, traditional electrical-optical-mechanical (EOM) cables are constructed from very high modulus materials such as aramid fibers (e.g. Kevlar) or polymer materials (e.g. Vectran). To implement these very stiff cables in a mooring application requires that compliance be provided in other ways, such as the geometric arrangement of the mooring or special, very stretchy sections in the mooring. An alternative is to design a stretchy EOM cable by spiraling the conductors around a low-modulus material at a high-enough helix angle to allow the cable to stretch without straining the conductors [4]. As described below, the MOOS mooring employs a high-modulus cable of relatively traditional design. As part of the collaboration between MBARI and WHOI, engineers at WHOI are currently developing a stretchy, polyester based EOM cable. A test deployment of this design will take place near Monterey Bay in October, 2005.

The MOOS mooring design is an inverse catenary design in which flotation attached to the mooring cable induces a S-shape in calm conditions. Figure 1 shows the mooring design, consisting of a buoy with total displacement of 6000lbs, a snubber section which resembles a heavy fuel hose about 8" in diameter, and a Vectran EOM cable that is supported by attached flotation to induce an inverse catenary shape to the mooring. Because of the very low stretch requirements of the optical fibers and copper

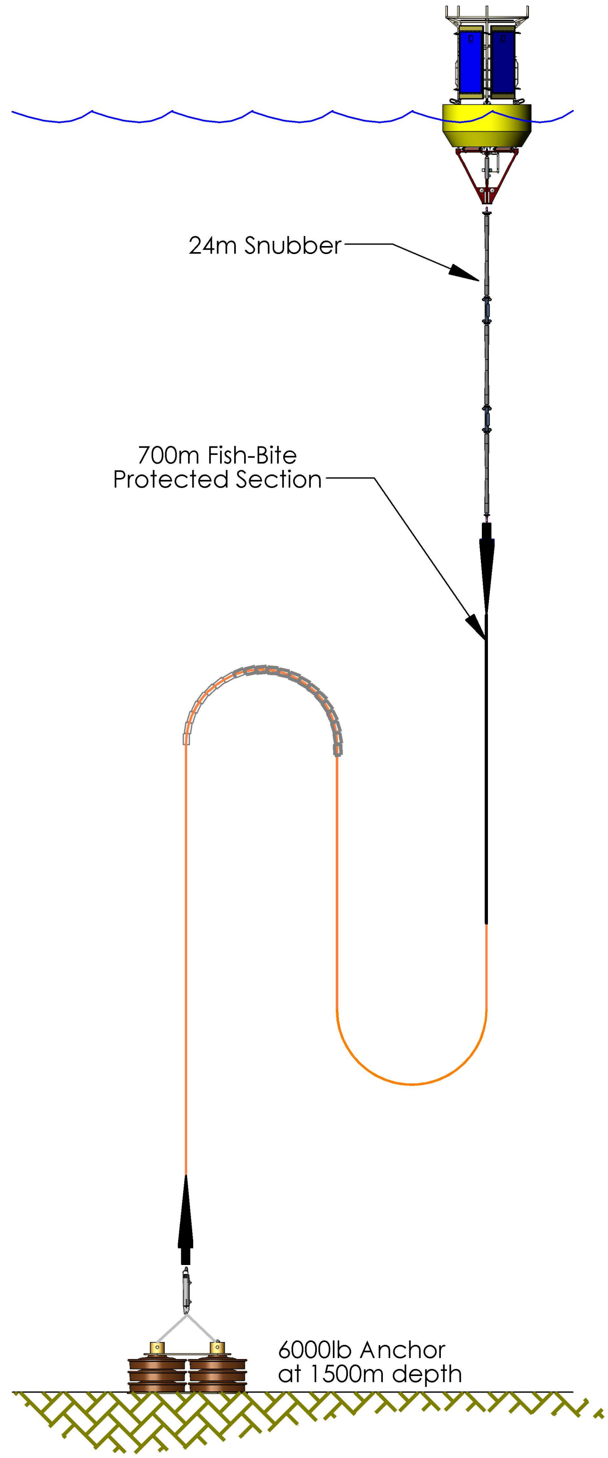

Figure 1. DIAGRAM OF MOOS MOORING SYSTEM SHOWING BUOY, SNUBBER SECTION, EOM CABLE ARRANGEMENT AND SUBSEA FLOTATION.

Table 1. ENVIRONMENTAL CONDITIONS AND RESULTING PREDICTED MOORING TENSIONS.

Condition	Significant Wave Height	Wind Speed	Surface Current	Tensions (Mean/Peak) Below Buoy	Tensions (Mean/Peak) Above Anchor
Survival Condition	9.8 m (16 s)	20 m/s	0.7 m/s	2530/4590 lbs	2150/4650 lbs
Design Condition	3.5 m (10 s)	10 m/s	0.35 m/s	1070/1870 lbs	680/1730 lbs

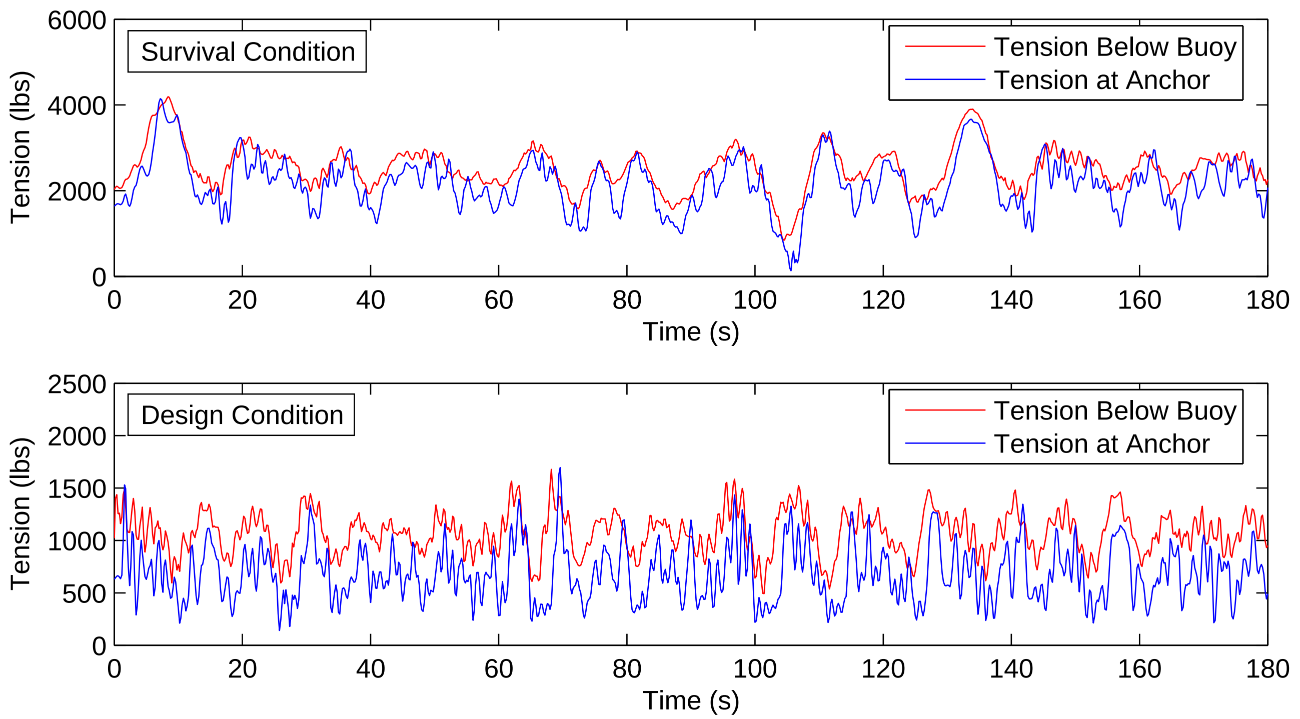

Figure 2. TENSIONS PREDICTED BY NUMERICAL MODELING FOR MOORING IN SURVIVAL CONDITION AND DESIGN CONDITION.

conductors, this S-shape does not provide enough compliance to the system in severe conditions. To provide additional compliance, the low-modulus "snubber" section is included below the buoy. This system is a WHOI design in which a "coil-cord" arrangement of fibers and conductors are housed within an outer stretch hose [5]. This snubber section extends 24 meters below the buoy, at this point the mooring transitions to the EOM cable, the upper 700 meters of this cable is protected from fish-bite by a stainless steel overbraid which adds slightly to the cable diameter and significantly to the cable weight. At the seafloor end, the optical and electrical conductors are brought out to an underwater mateable connector for connection to a sub-sea instrumentation network via remotely operated vehicle.

The system illustrated in figure 1 was deployed outside of Monterey Bay in April, 2004, and has been reliably reporting data through the California winter storm period. The mooring is scheduled for recovery in April 2005.

The final MOOS mooring design is the result of many tradeoffs between requirements regarding buoy size, instrumentation payload, power-gathering capability (solar and wind), operational considerations and reliability concerns. The numerical modeling techniques described in the next section were used to evaluate the design space and to settle on the final design and configuration.

MOORING SYSTEM MODELLING

Extensive numerical modeling of the mooring system was completed as part of the design process for the mooring. To perform the analysis, the equations of motion of the mooring system are solved in the time domain by utilizing the *CABLE* software developed at WHOI [6]. The mooring system is described by specifying the properties of the buoy and each section of the mooring; axial and bending stiffness specification, mass, axial and normal drag coefficient, axial and normal added-mass coefficient, and diameter are included. Where possible, the properties for each element in the system are determined by testing of the actual elements. This is straightforward for the axial stiffness, mass, and diameter. Bending stiffness is harder to measure accurately for the synthetic EOM cable because the cable doesn't always behave elastically in bending, but rather tends to take a 'set' when bent. Estimates are made but this is a source of potential error in the model. The axial elasticity of the snubber section is also not linear, the elastic behavior of the snubber has been measured and this nonlinearity is incorporated into the model. Characteristics such as drag and added-mass are not measured, but the classical estimates of these parameters for long cylinders seem quite appropriate.

In the model, environmental loading is specified as surface wave characteristics, wind conditions and a current profile throughout the water depth. The finite-difference solution of the equations of motion is performed in the time-domain and in three-dimensions, allowing the inclusion of direction information in the environmental loading specification. The solution includes tension and motions along the length of the mooring system. For this solution, the model of the mooring string is forced dynamically by the wave motion. A wave form in the time domain is selected that has a spectra with specified significant wave height and peak period. Wind and current forcing are static forces, unchanging during the time-simulation.

The buoy itself is 2.3 meters in diameter and has a mass of 1500 kg. For the dynamic modeling, the buoy is assumed to be a perfect wave follower, which is appropriate as its natural frequency in heave is higher than the frequency of the expected wave exciting forces. The *CABLE* software mimics the wave following situation by forcing the vertical velocity of the buoy in a manner that matches the vertical velocity of the wave-field. The buoy is free to surge and sway, and the resulting motions are found by integrating the buoy (and mooring) equations of motion in time. In this approach, the hydrodynamics of the buoy/wave interactions are not modeled, a potential source of discrepancies between modeled and observed results. In the design of the mooring system, no buoy shape optimization was done with regard to its dynamic response in waves, the size and shape of the buoy is a result of tradeoffs between payload capacity, stability requirements and operational requirements that limit the buoy size.

Figure 2 shows predicted tensions at the anchor and below the buoy for the final mooring design in two loading conditions. The "survival condition" corresponds to the conditions expected in a "25-year" storm, as estimated by statistical analysis of the observed wave heights over 17 years at NDBC buoy #46042, located outside Monterey Bay near the test deployment site. This analysis consisted of fitting a Wiebull distribution to the NDBC buoy observations, which are made every hour, and computing the probability of various wave heights based on this distribution. The "design condition" represents the condition that will only be exceeded 10% of the time, based upon the same statistical analysis. Table 1 summarizes the environmental conditions and the predicted tensions in each condition. The surface current conditions are estimated from current measurements made via acoustic Doppler measurements at MBARI moorings in Monterey Bay. For the design work, the wind, waves, and currents are all assumed to be from the same direction. This represents a possible worst case for maximum tensions, but the dynamics of the mooring may be significantly different if the wind and waves are from a different direction from the currents, which is possible. This type of three-dimensional analysis is performed for the comparison work. Because of the limited duration of the simulations, the maximum tensions listed in this table are computed as the mean tension plus four times the standard deviation of the tension results over the simulation period. These predicted tension results were used to specify the requirements on the EOM cable, which was designed for a maximum working load of 6000lbs. The limiting factor for the cable design is a low stretch requirement on the electrical and optical conductors, $<0.6\%$ to ensure extended life of these elements.

The use of this high-modulus material as mooring cable introduces several concerns that are evident in the predicted loading results of figure 2. There is little damping of high-frequency energy evident, the results for the design condition waves indicate a potential resonance feature. Interestingly, in the storm condition, there is less high-frequency energy near the buoy than near the anchor. This is the opposite of what one would expect for a typical mooring system forced by waves at the buoy end and is likely related to the presence of the low-modulus snubber element below the buoy, which is not present at the anchor end.

MEASURED TENSIONS AND MODEL VERIFICATION

The test mooring currently deployed is equipped with instrumentation to monitor the environmental loading on the system and measure the resulting mooring line tensions. An aim of this instrumentation is to allow the verification and refinement of the numerical model. Instrumentation is present to measure all three of the environmental inputs to the model; wind, wave and current forcing. Wind measurements are made continuously on the buoy and ten-minute averages and 5 second maximums are reported and stored. The numerical model does not include the effects of variable winds, and only the average values are used in the model comparisons. Wave measurements are made by a directional wave sensor on the buoy, every thirty minutes this sensor reports significant and peak wave heights, the period of the waves at the peak of the wave spectra, and wave direction and spreading. Current measurements are made by an acoustic Doppler current profiler mounted below the buoy. The resulting

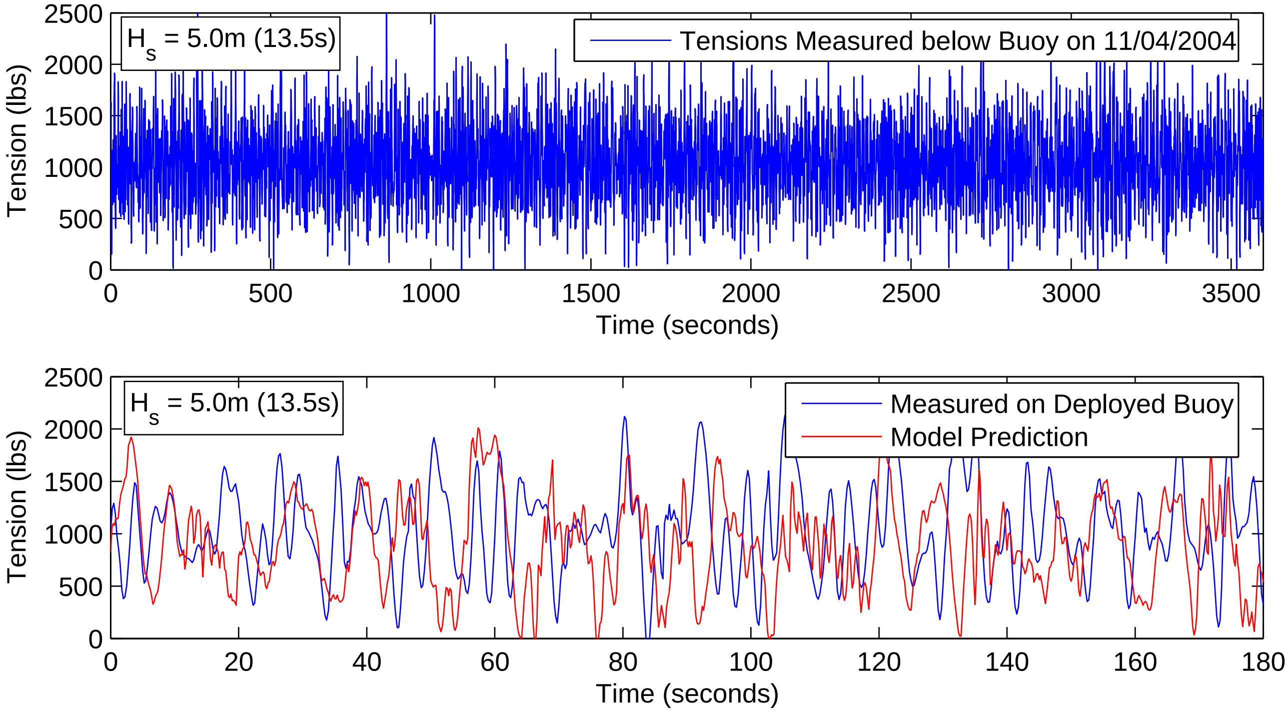

Figure 3. COMPARISON OF MEASURED AND PREDICTED TENSIONS BELOW THE BUOY. SIGNIFICANT WAVE HEIGHT = 5 METERS (13.5 S) AT 150 DEGREES, 30 CM/S SURFACE CURRENT TO THE WEST, AND 10 M/S WINDS FROM 180 DEGREES.

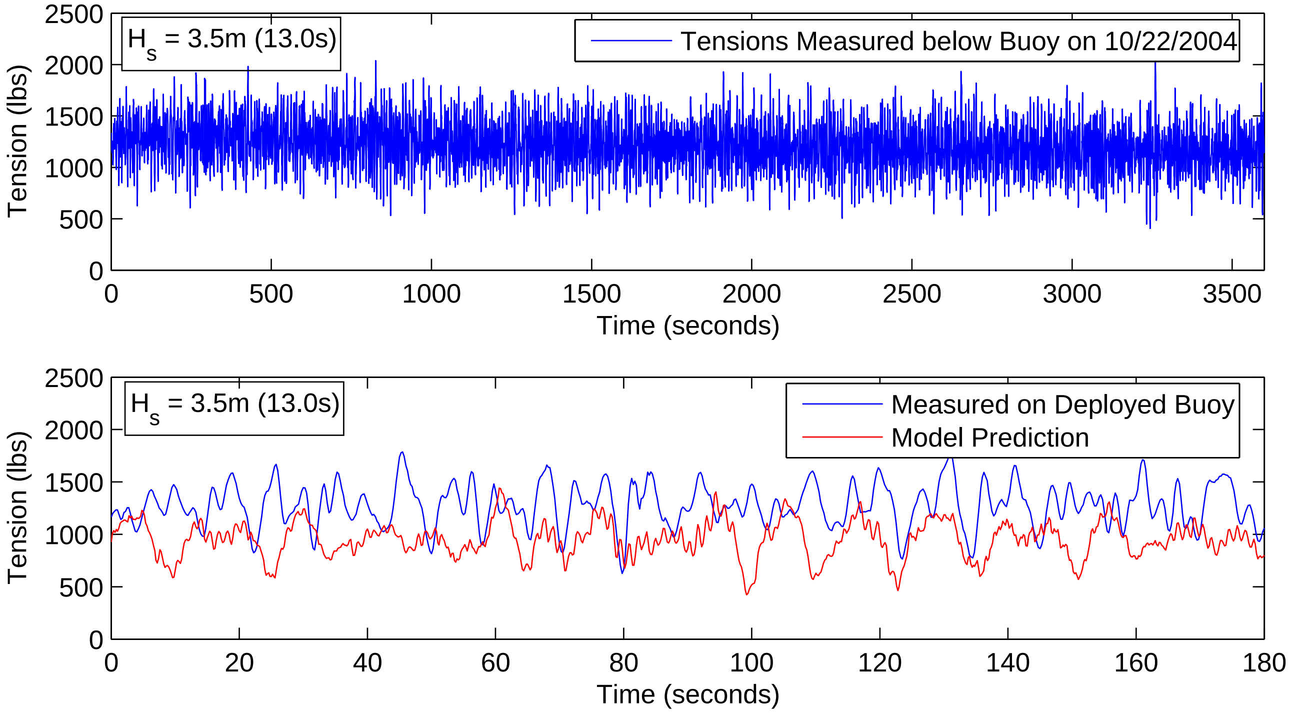

Figure 4. COMPARISON OF MEASURED AND PREDICTED TENSIONS BELOW THE BUOY. SIGNIFICANT WAVE HEIGHT = 3.5 METERS (13.0 S) FROM 330 DEGREES, 45 CM/S SURFACE CURRENT TO THE NORTH-WEST, AND 7 M/S WINDS FROM 350 DEGREES.

Table 2. COMPARISON OF MEASURED AND PREDICTED TENSIONS BELOW BUOY FOR TWO CONDITIONS.

Date	Significant Wave Height	Mean Wind	Mean Tension Pred./Meas.	Minimum Tension Pred./Meas.	Maximum Tension Pred./Meas.
11/04/2004	5.0 m (13.5s)	10 m/s	890/1040 lbs	-105/-135 lbs	2010/2190 lbs
10/22/2004	3.5 m (13.0 s)	7 m/s	950/1280 lbs	420/630 lbs	1440/1790 lbs

current profile has a bin size of 8 meters, extends down to 500 meters below the surface, and is reported every hour. The currents below this point are unknown, and are estimated as a linear decay from the current at the 500 meter depth down to zero at the sea-floor (1500 meter depth). This assumption is questionable, and unfortunate because the mean loads predicted by the model are heavily influenced by the current profile. Acoustic current meters stationed at the surface are limited to a 500 meter depth and placing instruments on the seafloor for this deployment was not feasible. The seafloor near the buoy deployment site is relatively flat, the significant canyons of Monterey Bay are a considerable distance away (10's of kilometers) and activity there is not expected to influence the deep currents at the mooring site.

The mooring is equipped with load cells just below the buoy (above the snubber), and just above the anchor. These load cells are recorded at 4 Hertz and the resulting data is logged on board the buoy. Summaries of this data (maximum and mean), are reported to shore every 10 minutes. Unfortunately, the lower load cell failed several months into the deployment, so measurements of the loads at the anchor are unavailable during the winter storm period. A small amount of the high-frequency data has been retrieved from the buoy via high frequency radio and is available for model verification.

To perform comparisons, the numerical model must be run with environmental inputs that match those that existed during the period the loads on the mooring are measured. Further, the directionality of the forcing mechanisms must be included. Where a two-dimensional model is suitable for design investigation, the verification model runs must be made in three-dimensions, allowing the wind, wave, and current directions to be included. The importance of this is evident in a comparison of buoy position with wind and wave data, the buoy is often observed to be upwind of its anchor due to current forcing.

Two conditions were selected for model comparisons, one with a significant wave height H_s = 5.0 meters and one with H_s = 3.5 meters. Figures 3 and 4 show a comparison between measured tensions below the buoy and the model prediction for each of these two conditions. In each case, the model was run with wind, wave, and current forcing that matched the conditions at the time of the measurement. The upper plot in each figure shows the measured tension over an entire hour, the lower plot superimposes a few minutes of this record and the model results for these conditions. It is important to note that there is no correlation in time between the actual wave forcing and that used in the model, other than the course estimates of significant wave height and peak period of the spectra. Because of this, it is not expected that the loading will match in time and statistical measures such as mean and maximums are most relevant. However the comparisons in the time domain do show the nature of the measured signal and highlight some features of the model results. Particularly, in both cases the model shows a tendency to report a higher frequency component that is not observed in the measured signals. Table 2 shows a statistical comparison between the modeled and measured tensions in the two conditions.

These model runs were made without changing the mooring system specification from the original values used during the design phase. It would be possible to tune the model to match the measured results more accurately, but this needs to be done in a way that improves the agreement across the entire range of conditions, not just at a few selected wind, wave, and current conditions. This may be possible when the complete loading data set is retrieved.

CONCLUSION

The numerical model of the mooring system produces results that match remarkably well with the loads measured on the test mooring, at least for the environmental conditions investigated here. This result is important for validation of the model, and its subsequent use for two main purposes, designing future deployments with this cable system, and informing the testing program designed to determine and extend the service life of these systems.

The development of an accurate and validated numerical model of the mooring system facilitates the deployment of the system in locations with different, and more severe, environmental conditions. Compared to polyester or nylon moorings, there is a relatively small amount of experience with moorings of this type that use a high-modulus synthetic material for a mooring cable.

Because of the high-cost of the EOM cables, the service life of the moorings must be several years at least. The numerical model, when accurate over a range of conditions, is a useful tool for understanding the long term loading the cables must endure.

In addition to predicting loads, the model has proven useful in estimating the cyclic bending conditions that exist in the mooring line. Bending is a known failure mode of the cables and an effort is underway currently to perform high-cycle laboratory testing of the cable designs. In conjunction with the results from the deployed test system, the model is being used to estimate the tension and bending characteristics of the cable over its lifetime, extrapolated from historical wind and wave loading at a particular site. The validation of the model performed here refines the accuracy of this effort.

Effects due to vortex-induced vibrations have not been considered to date, and the numerical results shown here do not include any modeling of these effects. When considering the fatigue life of the cable, it may be important to include the higher frequency loading on the cable due to these effects. The mechanics of how this type of vibrations damage and weaken the cable over time are likely different than the mechanisms currently being explored (bending and axial tension cycling). If, after more field deployments, the service life estimates are not found to match the estimates provided by the current testing program, it may become necessary to include these effects, but this is not planned at this time.

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