Dynamic Modeling and Actual Performance of the MOOS Test Mooring

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Abstract— **This paper presents a comparison between model predictions made with WHOI-Cable and actual measurements of the tensions in a deep-water oceanographic mooring. The mooring is part of the MBARI Ocean Observing System (MOOS) that utilizes an electro-optical-mechanical (EOM) cable to deliver power and communications to a sub-sea network of instruments. The predictions agree acceptably with the measured results, and improvements to the model and validation system that will be incorporated in the next deployment are discussed. Also presented is an outline of the information learned about the mooring cables service environment, both from the deployment results themselves and from the cable dynamics model.**

I. Introduction

In December 2002, the Monterey Bay Aquarium Research Institute (MBARI) deployed the first prototype mooring of the MBARI Ocean Observing System (MOOS) [2]. This mooring is a deep-water oceanographic mooring designed to deliver power, data and time signals to the seafloor in support of the MOOS sub-sea network of instrumentation (see figure 2). The mooring system is sized to be deployable from regional class UNOLS vessels and relies on energy gathering (solar, wind and potentially wave) techniques to provide up to 40W of power. Satellite communications technology provides a low-bandwidth path from the buoy to shore while the mooring itself is designed to provide a high-bandwidth communication path from the buoy to the seafloor. The power and data transport is accomplished through an electro-optical-mechanical (EOM) mooring cable-riser system specially designed and built for this application. Figure 1 shows the mooring being deployed from the Point Sur on December 2, 2002.

The purpose of the prototype mooring was to test several aspects of the design and to validate modeling of the mechanical loads on the system during deployment and operation. The mooring's ability to harvest solar power using large-area vertical arrays, and harvest wind power using an off-the-shelf wind turbine, was also evaluated. High risk elements of the design that were tested included the survivability of the copper conductors and optical fibers in storm conditions, the performance of the solar and wind power collection system, and the moorings tendency to twist up, which would make the connections to a fixed sub-sea network more difficult.

During the design phase, cable dynamics modeling was performed using the Wood's Hole Oceanographic Institute's "Cable" software [1] to predict the loads in the system in various sea conditions. To allow validation of this model, the mooring system was equipped with load cell instrumentation to measure the actual tensions in the mooring cable on a continuous basis. The purpose of validating the modeled results is to increase the level of confidence with which the cable model can be used to predict field loads.

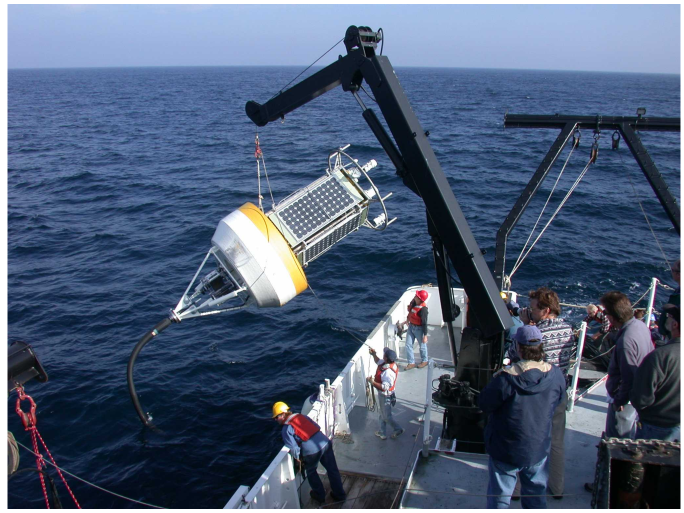

Fig. 1
Buoy Deployment from the Pt. Sur, December 2, 2002.

Unfortunately, the EOM cable in this mooring system parted in a storm on December 15, 2002. The sea conditions at the time of failure approached, but did not attain, the 25 year storm conditions that were the maximum conditions the mooring was designed to survive. Subsequent recovery of all mooring components has allowed for a complete failure analysis to be performed, the results of which are being used to improved the design of the system.

In spite of the cable failure, valuable data and experience was obtained that allows some validation of the cable model and indicates changes in the data acquisition system necessary to improve the validation effort in the next deployment. The continual improvement of the mooring model is an important goal of the project, allowing the MOOS system to be deployed confidently at new sites, based only on some knowledge of the sea-states likely in that area.

This paper presents the measured tension data collected during the deployment and makes comparisons to the predicted results obtained from the WHOI-Cable model. Results are compared for both the actual mooring installation phase and the operation phase of the deployment. An overview of the failure analysis is also presented and the cable dynamics model is again used to illuminate aspects

Sea State	Outer Monterey Bay	California Coast	NE Pacific Rise	Juan de Fuca	Station P
25-Year Return	9.8m (16s)	13.0m (19s)	8.2m (14s)	14.0m (21s)	14.5m (22s)
10-Year Return	9.3m (15s)	12.4m (18s)	7.8m (14s)	13.2m (19s)	13.8m (20s)
90% Design	3.5m (10s)	4.5m (12s)	3.5m (10s)	4.7m (12s)	4.8m (12s)

TABLE I

Expected sea-states at target deployment sites. Significant wave heights and peak periods are shown.

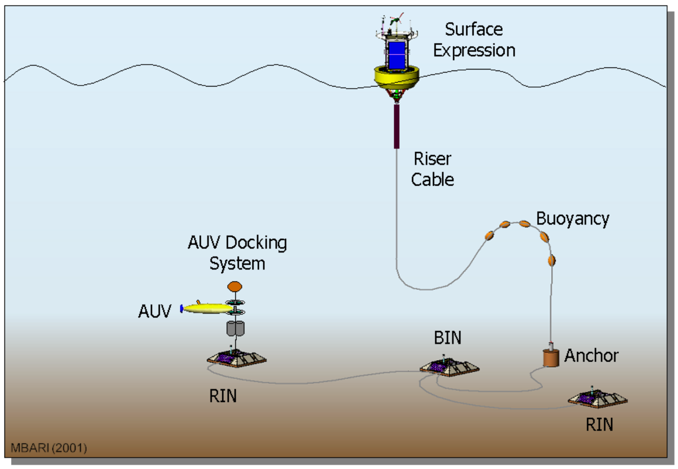

Fig. 2

Schematic of the MOOS mooring system and associated benthic network.

of the loading conditions of the riser cable that must be considered in designing a cable for this application.

II. MOOS Mooring Description

The MOOS Mooring is a inverse-catenary type deep-water mooring that relies on floatation attached to the mooring cable to induce an S-curve in the mooring line which keeps the mooring cable free of the bottom and provides the required compliance to allow the surface expression to ride over waves and swells. The surface expression itself supports panels for solar power collection with a total area of 1 m^2, a wind driven generator, satellite communication hardware and control electronics to synchronize all the measurements, reduce data, and transmit data to shore. Figure 2 shows a schematic of the MOOS Mooring system and illustrates the connection to the planned benthic network of instrument nodes. Because the optical fibers and copper conductors can not endure any strain beyond about 0.5%, the cable itself must have a very high axial stiffness and is made of high-modulus aramid fiber. This high axial stiffness in the cable necessitates a compliant "snubber" element below the buoy to reduce the peak axial tensions in the system and provide increased durability of the riser system near the sea-atmosphere interface. The snubber resembles a fuel hose and was designed specifically for the MOOS system by Walter Paul at WHOI. Inside the snubber assembly is a specialized "coil-cord" conductor package that resembles the cord of a telephone handset [3], [4]. This coil-cord provides the conductor compliance required in the 16 meter snubber which may stretch up to 50%.

The entire system is designed to be deployable in water up to 4,000 meters deep, in a wide variety of ocean environments. The initial target sites are shown in table I where the survival condition shown is the storm likely to occur once in 25 years. The design condition is the condition that is only expected to be exceeded 10% of the time. The system is designed for a life of three years, with yearly maintenance trips that include replacing the surface expression and snubber assembly. These elements are designed to be replaceable in the field without retrieving the EOM cable and benthic network. The prototype mooring was deployed in Monterey Bay near Moss Landing, California where the conditions are well represented by the "Outer Monterey Bay" site.

In order to validate the cable-dynamics model, the mooring riser is equipped with load cells just above the anchor and just below the buoy. These load cells are sampled at 4 Hz and a reduced data set is transmitted to shore periodically (every two hours). The buoy heading is also measured, this data is important to evaluate the moorings tendency to twist up. Also measured and transmitted to shore is data reflecting the performance of the solar array and wind turbine. This information is important for characterizing the total power capabilities of the mooring over long term seasonal variations in weather conditions.

III. WHOI-Cable Dynamics Model

The WHOI-Cable software solves the equations of motion for the mooring riser in the time domain. The configuration of the mooring riser is specified in terms of the material properties (mass, size, modulus, etc.) of the various segments of the riser system. Environmental inputs to the model include a description of the sea-state, wind conditions, and current conditions. The MOOS riser is a fairly complicated system that has a variety of segments, ranging from the high modulus synthetic cable for most of the length to the very elastic snubber section for a short length near the surface. Accurately modeling all of these components is a significant effort; some characteristics such as mass, size, and axial stiffness are easily measured, but others like the bending stiffness of the cable, and the nonlinear axial stiffness of the snubber are more difficult to estimate. The long-term goal of the validation effort is to use the results measured at sea to refine the riser characterization in the model to provide results that are accurate over the entire range of conditions. The short duration of the first deployment precluded this and the results below only show comparisons for two different environmental conditions.

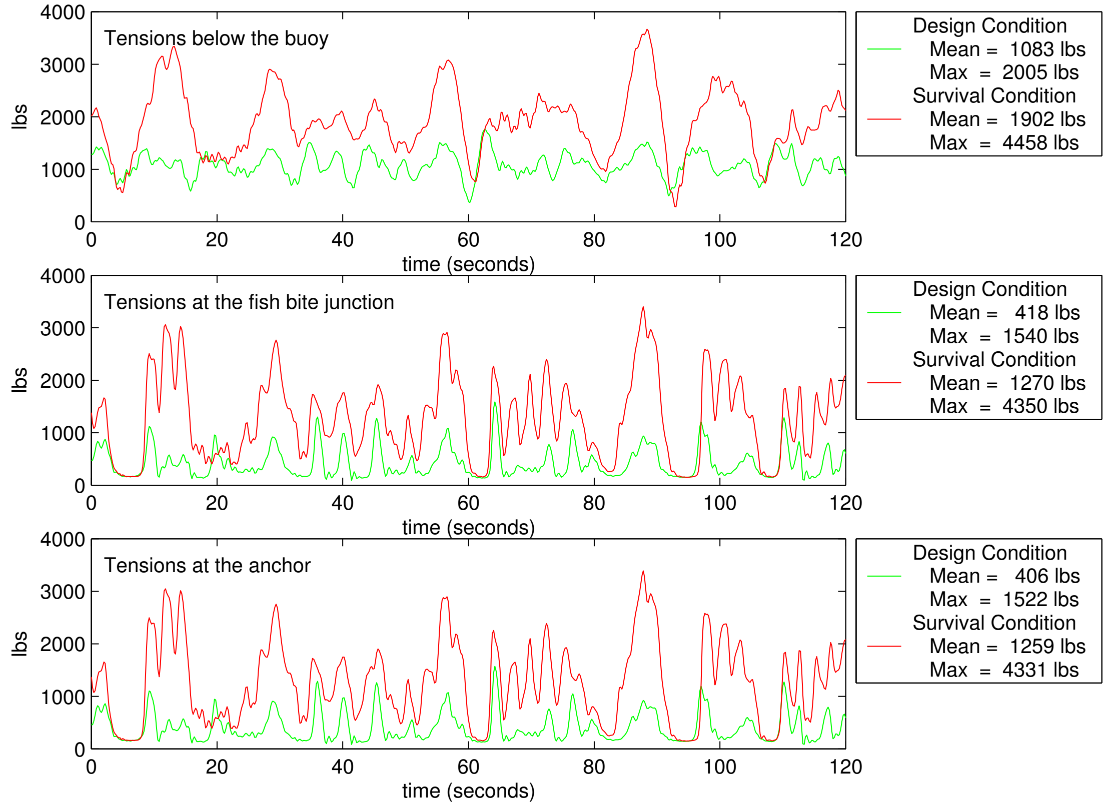

Fig. 3
Predicted tensions on riser cable in the survival and design sea conditions.

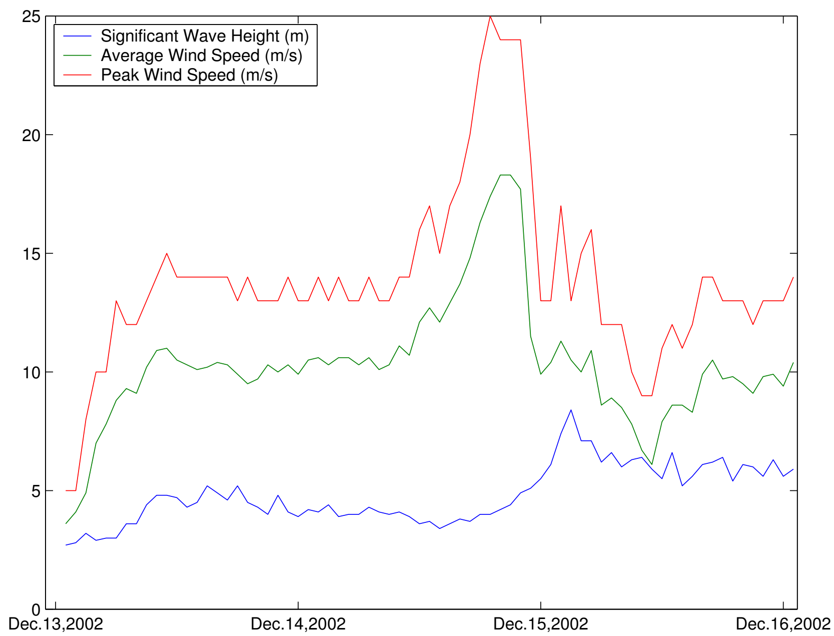

Fig. 4
Measured wind and wave conditions during the storm of December 13-16, 2002.

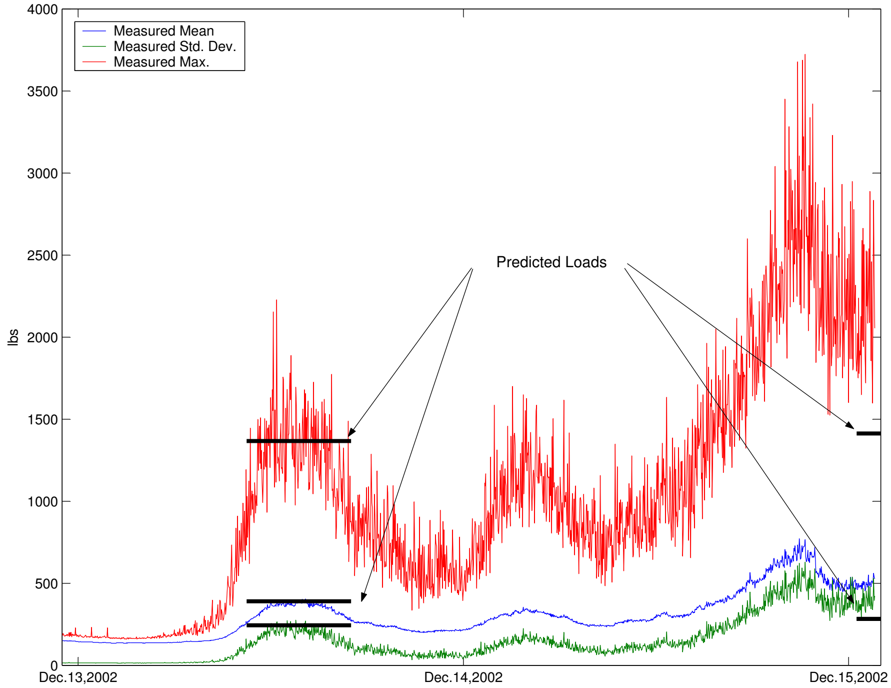

Fig. 5

Measured and predicted tensions in the riser just above the anchor (Mean, max, and standard deviation computed for two minute windows).

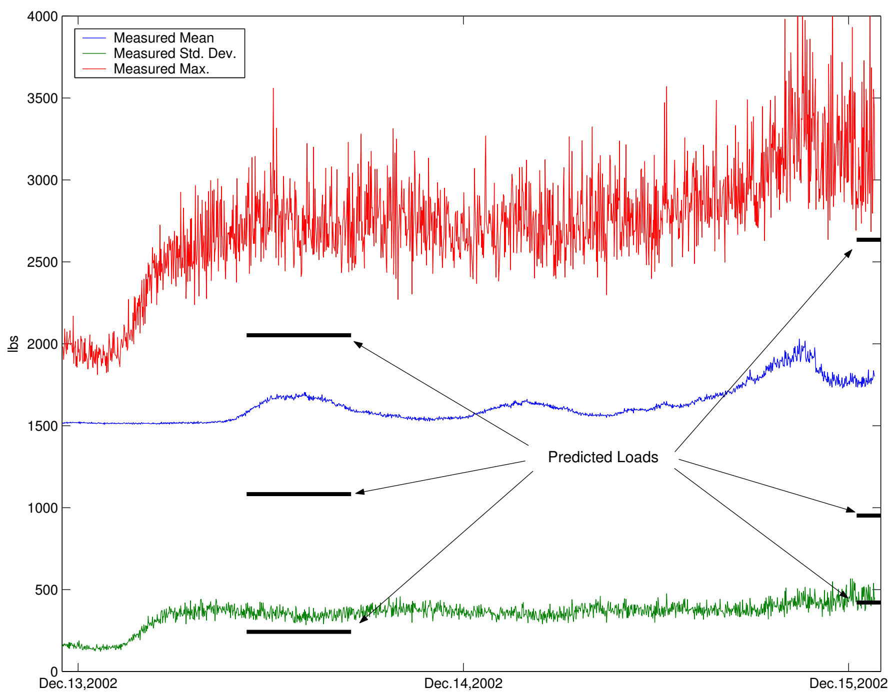

Fig. 6

Measured and predicted tensions in the riser just below the buoy (Mean, max, and standard deviation computed for two minute windows).

IV. Mooring Load Modeling and Comparison to Measurements

As part of the mooring design, the WHOI-Cable model was run for the 25 year storm condition and the 90% design condition at the Outer Monterey Bay site (table I). Figure 3 shows the resulting predicted tensions at the anchor, below the buoy, and at a point 750 meters below the buoy where the fish-bite protection on the cable ended. This analysis indicated that the resulting tensions would always remain below the 6,000 lb working load of the cable. Load cells at the anchor and below the buoy in the deployed system provide an opportunity to validate these predictions. In order to do this however, the model must be re-run for the actual conditions present, which vary over time. Figure 4 shows the wind and wave conditions during the storm of December 13-16. These wave and wind conditions were measured at the nearby NDBC buoy #46042, which was located about 5 miles from the MOOS mooring location. Maximum significant wave heights of 8.4 meters remained below the designated survival condition. To evaluate the WHOI-Cable model's ability to predict the loads, the model was re-run (unchanged in all other ways) for the sea-state conditions during the storm. Because the sea, wind and current conditions were being measured at a site away from the buoy, one of the sea states selected for modeling was the condition that persisted for a relatively long period of time during the two day storm. The other condition selected for modeling was the peak sea condition that occurred. Figure 5 and 6 show the comparison between the measured and predicted tensions at the anchor and below the buoy respectively. Because the 4 Hz load cell data that was collected on board the buoy was reduced to a mean, max, and standard deviation of the measurements over two minute periods, it is necessary to reduce the model results in the same manner for comparison.

V. Deployment Load Modeling and Comparison to Measurements

Also predicted by the cable model were the tensions in the system during the deployment. For operational convenience and safety, it is desirable to perform the deployment in an "anchor-last" manner. In this procedure, the buoy is placed in the water, cable is payed out as the deployment ship steams ahead slowly, and finally the anchor is released from the ship. The resulting free-fall of the anchor to the seafloor requires confidence that the working load limit of the cable (6,000 lbs) will not be exceeded. Also, the accuracy with which the anchor may be placed on the seafloor needs to be determined to assess the suitability of this method for installation of the mooring and subsequent connection to a benthic network.

Figure 7 illustrates the predicted mooring-cable configuration at successive time-steps as the anchor falls to the seafloor. An acoustic transponder on the anchor allowed two measurements to be made to validate this prediction. First, the range to the transponder was continually monitored from the ship during the anchor descent and the total time to the bottom determined by measuring the time required for the anchor to stop descending. The descent took 10.5 minutes compared to 10.9 minutes predicted. After the anchor settled into position on the bottom, a long baseline survey of the transponders position was conducted and the position compared to the ships position at the time the anchor was released. This measurement indicated the anchor "fall-back" was 210 meters, compared to 229 meters predicted by the cable-dynamics model. This excellent agreement between the actual deployment and the model is encouraging for the suitability of the anchor-last deployment method for this system. However, the day of the deployment was very calm and further deployments with similar measurements are required to provide enough information to develop a probability distribution of placement accuracy around the target location.

Figure 8 compares the predicted and measured tensions during the deployment. Although the tension variation throughout the deployment does not match particularly well, the maximum load experienced was predicted accurately and falls within the 6,000 lb limit, above which damage to the optical fibers is likely.

VI. Failure Analysis

The parting of the cable after only a short time in the water was unexpected and a considerable effort has been undertaken to analyze this failure to determine what improvements to the system are needed. At no point did the tension measurements made at the buoy or the anchor exceed about 4,000 lbs, below the 6,000 lb safe working load of the cable and well within the 36,000 lb breaking strength of the new cable. This indicates the cable was damaged in some way and not that the loads in the system were dramatically higher than expected. Recovery of both the upper and lower pieces of the mooring riser was accomplished by MBARI's R/V Point Lobos and ROV Ventana. The break took place about 850 meters above the anchor, in the middle of the riser cable and at the highest point of the S-curve shape that occurs in calm conditions. Analysis of the Kevlar fibers at the break site suggested that the fibers had been damaged by repeated low-tension bending, leading to kink-band formation in the fibers. Presumably, this type of bending occurs at the edge of the floatation elements clamped to the cable and a more significant bending strain relief is needed to maintain a minimum bend radius at the float attachment point.

The WHOI-Cable model provides insight into the requirements of such a bending strain relief. Figure 9 shows the model results near one particular float in one particular moderate sea state (Significant wave height = 1.5 meter, Period = 10 seconds). The top graph shows the angle from horizontal of the cable at the float, just above the float and just below the float. Clearly, significant bending at the float attachment point is predicted by the model. The middle graph illustrates the relationship between the tension in the cable at the float and the bend angle. The inverse relationship between tension and angle is clear, when

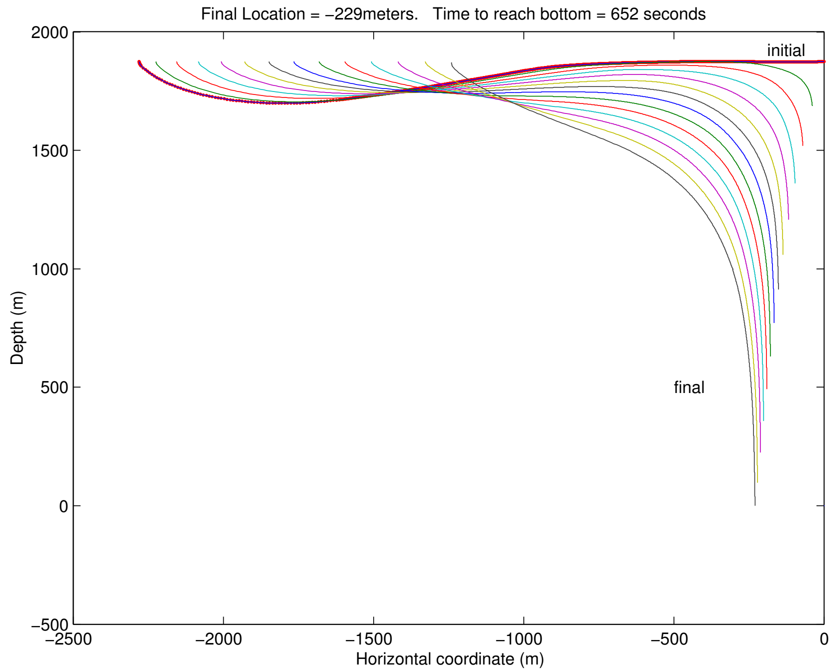

Fig. 7

Predicted configuration of mooring cable during anchor free-fall deployment, initially the anchor is on the ship at the surface and each successive line shows the mooring cable as the anchor free-falls to the bottom.

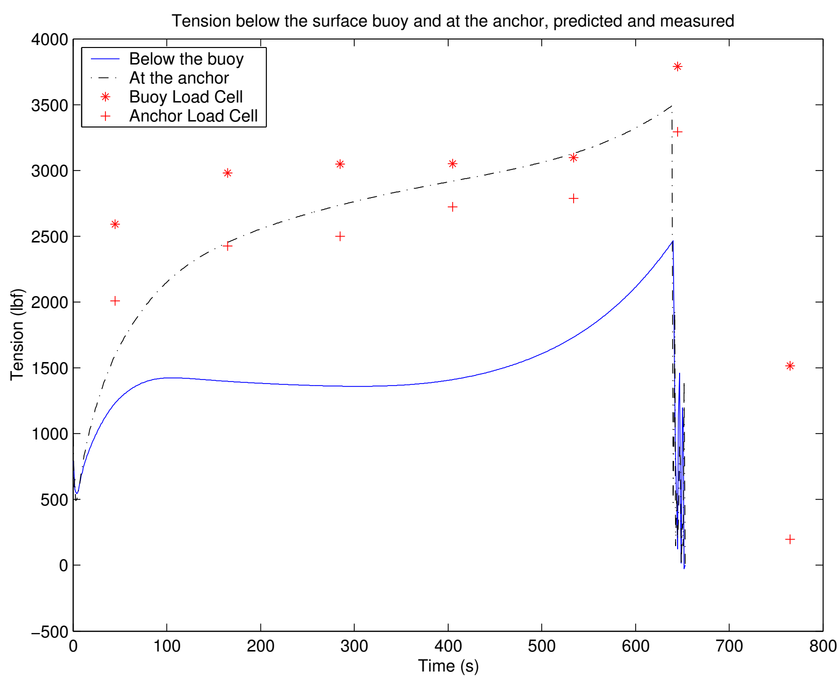

Fig. 8

Measured and predicted tensions during the anchor free-fall.

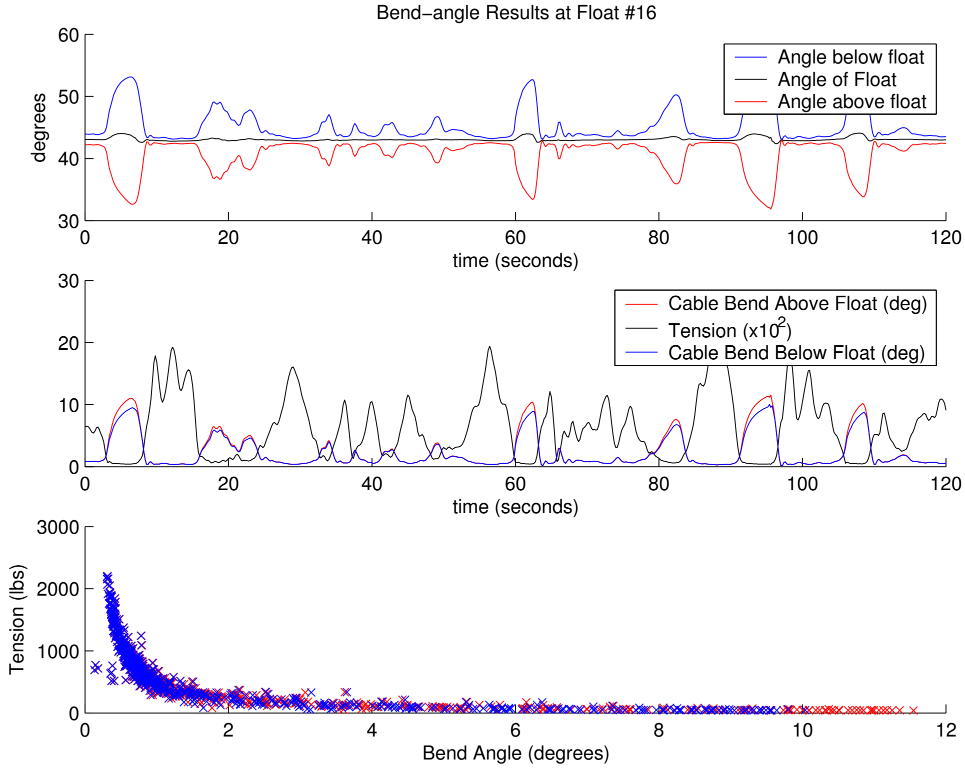

Fig. 9

Model results showing repetitive bending at float attachment points. **Top:** Time history of cable orientation during wave excitation. **Middle:** Variation of bend angle and cable tension. **Bottom** Bend angle versus tension relationship.

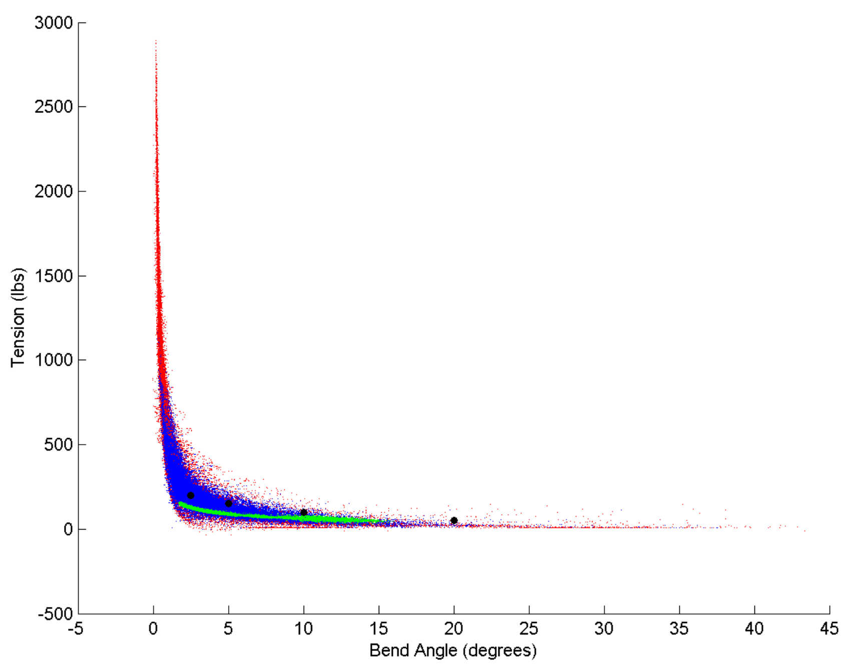

Fig. 10

Bend angle versus tension relationship for all float locations in all sea conditions.

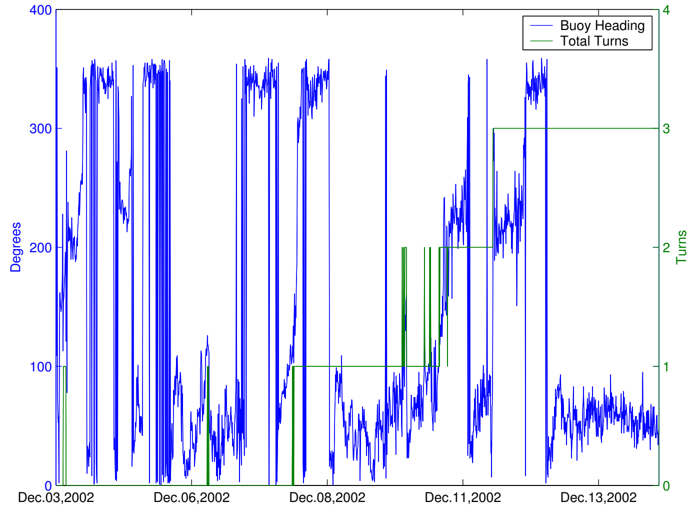

Fig. 11
Buoy heading and total turns during the deployment.

the cable goes slack, a large bend occurs, when the cable is pulled tight, the cable straightens. The period of this bending matches roughly the period of the wave exciting, meaning that millions of bending cycles per year will occur at the float locations. The bottom graph plots the tension versus bending relationship at each time-step of the model simulation. To design a bending strain relief for the float attachments, it is necessary to consider the bending at all of the float locations in all sea conditions. The cable model was run for the entire range of sea-conditions expected at the Outer Monterey Bay site in a year and figure 10 shows a plot of the bend versus angle relationship for all the float locations. The blue markers represent the conditions that occur 90% of the time, the red markers show the storm conditions which occur 5% of the time, and the green markers show the calmest conditions that occur 5% of the time. The black circles plot the bend versus tension relationship determined from static tests in MBARI's test tank. Because of the millions of bend cycles that will occur during the lifetime of the system, the cable and float system must be designed to withstand this repetitive bending.

VII. Buoy Rotation

Figure 11 shows the buoy heading and the total number of turns the buoy underwent during the deployment. The buoy performed three complete rotations during the deployment. At this rate, the rotatioin would pose a problem in the long term. However, the short duration of the deployment precludes any conclusion from these results, it is unknown if the rotation resulted from environmental forcing or simply from the relaxation of twists that existed in the cable or were induced into the system during the deployment. Similar heading data will be collected on subsequent deployments in order to answer this question. There is no evidence that this rotation contributed in any way to the cable failure.

VIII. Conclusion

The cable dynamics modeling of the MOOS Mooring with the WHOI-Cable software was generally successful in predicting the maximum axial loads in the system. The maximum loads during the anchor free-fall deployment were similar to those predicted and the tensions at the anchor matched very closely the predicted loads at the anchor end of the riser cable. At the buoy, the predicted loads were below the measured loads. Possible reasons for this discrepancy are a mis-estimation of the environmental conditions at the buoy location, and/or inaccuracies in estimating the material characteristics of the elements of the riser system. These results show the need to measure the wind, wave and current conditions at the buoy more accurately, and to use data from a longer deployment to adjust the model to give results that are valid over a range of conditions. If this is possible, it should enhance the confidence with which the MOOS mooring may be deployed in new locations. The failure of the mooring cable has led to new insights into the loading environment this mooring cable must endure in its lifetime, and will lead to an improved design. Quite a bit of valuable information was learned through this short deployment, and MBARI intends to deploy an improved system in late fall 2003.

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