Power producing buoy for strategic applications: Design Trade Study – Final Report

Grant No. HR0011-09-1-0032

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Project Period: 2/9/2009-9/8/2009

Summary

The purpose of this project has been to perform the first steps of an investigation of concepts and prototypes for extracting wave energy on an autonomous platform that remains on station in the ocean without being moored. The approach taken has been to develop a numerical model based upon rational mechanics of wave-body interactions for various candidate concepts. The effort undertaken in this project is meant to enable a larger companion project and thus is limited to the development and validation of the numerical model. The use of this model as a design tool is performed in the companion project. The numerical model solves the equations of motion of one or more connected rigid bodies floating in the ocean. The solution is performed in the time-domain and the result of the model is time histories of quantities of interest such as forces, motions and power converted by generators of different types. Because of the complexity of the problem a number of assumptions about the behavior of the system and the ocean waves are required to make the problem tractable. Because of this it is important to validate the results of the numerical tool against experiments before using the model as a design tool. Such an experimental validation has been performed as part of this project and the final results are presented in this report.

In addition to the technical work performed in this project, a number of other meetings have taken place that also contribute to the companion project, these include a technical and programmatic meeting at MBARI with the technical contributors and larger team. Additionally, two visits to other institutions have been made under this project to investigate the suitability of available technologies to this project.

Activities

1. Held a technical meeting at MBARI with subcontractors Airflow Sciences, Marine Innovation and Technology, and consultant William Webster: March 11, 2009.
2. Held a project kick-off meeting with DARPA personnel: April 16, 2009.
3. Completed a global environmental-condition analysis.
4. Visited Roy Kornbluh at Stanford Research Institute (SRI) to discuss the applicability of their “artificial muscle” technology to this application.
5. Visited Sid Chao at CIIIS to evaluate the applicability of the “ferro-fluid” linear generator system to this project.
6. Completed the development of a general purpose computer code for modeling wave-body interaction problems.
7. Designed and built a test buoy system for validating the computer model.
8. Performed a “step-response” test with test buoy in the MBARI test tank.

Technical Results

Numerical Model Development

A significant results of this project is the development of the computational framework needed to perform time-domain simulations of the various concepts under consideration for a station-keeping wave-energy conversion device. These concepts all require very similar modeling capabilities to analyze; all devices involve a floating body in waves and a device to harness energy from the relative motion of two or more bodies. The framework developed effectively solves for the motion of one or more bodies that are acted on by outside forces such as the wave field, currents wind, and any wave-energy extraction devices included in the system. This computational toolbox that has been developed is modular enough to allow various elements such as floating buoys, submerged foils, linear power take-off generators, submerged turbines, and wind turbines to be combined in nearly any arrangement. Adding new elements to the system requires only defining the forces that act on that element as a function of the elements position history throughout the time-domain simulation.

The analysis of such systems is fundamentally straightforward and involves the solution of Newton’s equations of motion (force = mass times acceleration). Although the solution of this type of equation is not difficult, the evaluation of the forces acting on the various parts of the system can be complicated. For example, the forces acting on a body floating in waves depends on the hydrodynamic behavior of the particular shape and size of the body. Further complicating this is the fact that as existing waves cause a floating body to move, this motion then causes the body itself to generate waves which add an additional force that acts on the body, further modifying it's motion. This feedback causes a "memory effect" in which the forces acting on the body at the current time depend not only on the body's current velocity, but also on the velocity history of the body. Fortunately, this complicated problem has been solved by previous researchers. (at least for linearized systems, which is an assumption made throughout this projects wave-body interaction numerical analysis and is one reason that subsequent validation of the simulation results via prototype or model testing is important).

The computer code to perform this analysis has been implemented in the Matlab programming language. The required wave-body hydrodynamic characterization of the floating body elements is computed using the WAMIT code. This code computes the linearized wave-body behavior in the frequency-domain, subsequent conversion to an impulse response function in the time-domain via Fourier transform is performed to include the WAMIT results in the time-domain code. This technique is fairly common for this type of problem and reduces the computational requirements significantly compared to solving the fully non-linear wave-body interaction problem. The result is a code that can simulate the wave induced motion of the prototype concepts in approximately real time, that is a 10 minutes simulation requires about 10 minutes of computer time on a typical desktop workstation. This relatively modest computational requirement is important for the current application which requires the simulation of many cases while varying parameters such as buoy size, wave size, power take off characteristics, etc. The computer code that has resulted from this project is called TD_xxx (this is a working name, and should probably be replaced with something more descriptive).

Although the techniques used in this code are well known, there are very few tools available that combine the techniques in the extensible nature of this code. In that regard the code itself appears to be fairly unique, in many discussions with other workers in the wave energy field it is clear that most don't have a tool such as this one at their disposal and that their efforts are hampered by the lack of an ability to predict the motions that their devices will undergo in the ocean environment. The TD_xxx code encapsulates most of the mathematics involved in the wave-body interaction problem and would allow non-experts to study their wave-energy concepts without a detailed knowledge of the wave-body interaction hydrodynamics. We have ideas of making this code available to a wider audience, but no such work has yet been undertaken.

Validation Tests

Because of the simplifying assumptions that are necessary, it is critical to validate the accuracy of the model against experimental results before using the model for design purposes. This has been done and the resulting comparison makes up the second major result of this project. To perform the validation a test buoy was designed and built that is similar in size to the expected concept designs. The response of the test buoy was measured over two days of testing in Monterey Bay, the tests where performed near an existing wave-measurement buoy that recorded the spectrum of wave heights present during the tests. Subsequently the numerical model was run with the measured characteristics of the test system (mass, dimensions, etc) and the wave input matching that which existed during the tests. The results from this comparison indicated that the numerical model faithfully replicates the important physics of the system and is useful for investigating the wave-energy concepts in mind.

The validation test buoy is shown in Figure 1 and consists of a surface buoy that is 96 inches in diameter and weighs 2600lbs. Submerged below this buoy is a flat, circular steel plate that is 48 inches in diameter and weighs 1300lbs. These two elements are connected by a 20 meter long tether and a 6 foot long hydraulic ram that operates as a spring/damper. One side of the hydraulic ram is plumbed to a system of accumulators that compress a gas as the ram is extended by the tension of the tether. These accumulators approximate a linear spring. The flow of hydraulic oil through the hoses and fittings introduces some damping also. These spring and damping characteristics have been estimated and are incorporated into the numerical model of the system. With this information, all important characteristics of the system are modeled, the buoy and plate mass, the buoy and plate hydrodynamic behavior, and the spring/damper characteristics.

A step-response test has been performed in which the buoy was lifted 12 inches above its static waterline and dropped. Because the buoy drops faster than the submerged plate, the ram is initially drawn in by the spring force provided by the accumulators. However, when the buoy reaches the bottom of its travel and starts back upward due to its buoyancy, the plate is still moving downward and the ram extends. The elongation and force history on the ram is the primary measurement made during the experiment and by comparing these to the motions predicted by the model, a validation of the model is accomplished. Figure 2 shows a photograph of the buoy in the MBARI test tank, the submerged steel disk is shown in the background of Figure 2 before deployment and submerged below the buoy in Figure 3. The top of figure 3 also shows the hydraulic cylinder between the buoy and the submerged plate in its static condition, extended about half-way due to the weight of the submerged plate.

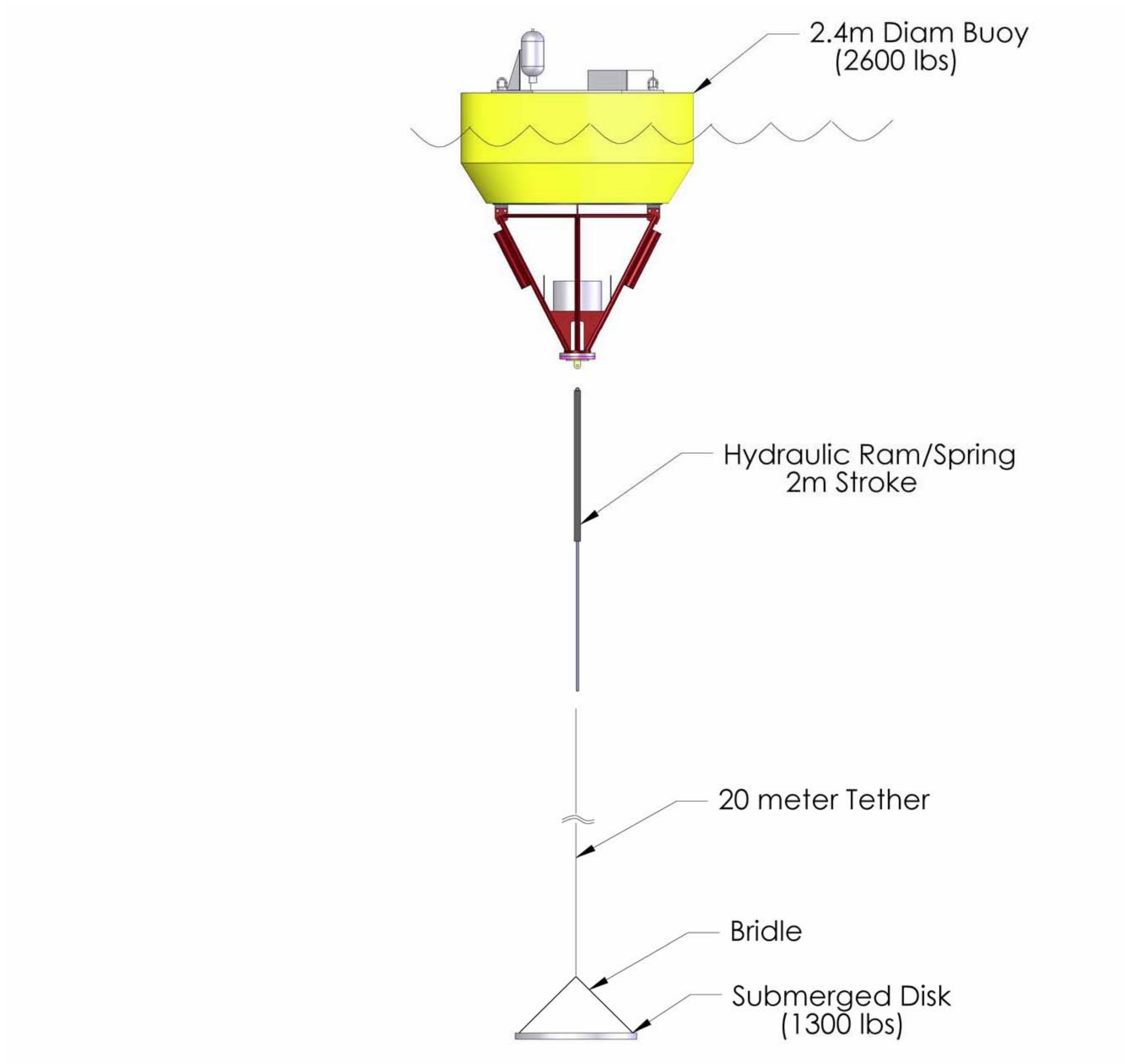

Figure 1: Diagram of test buoy system.

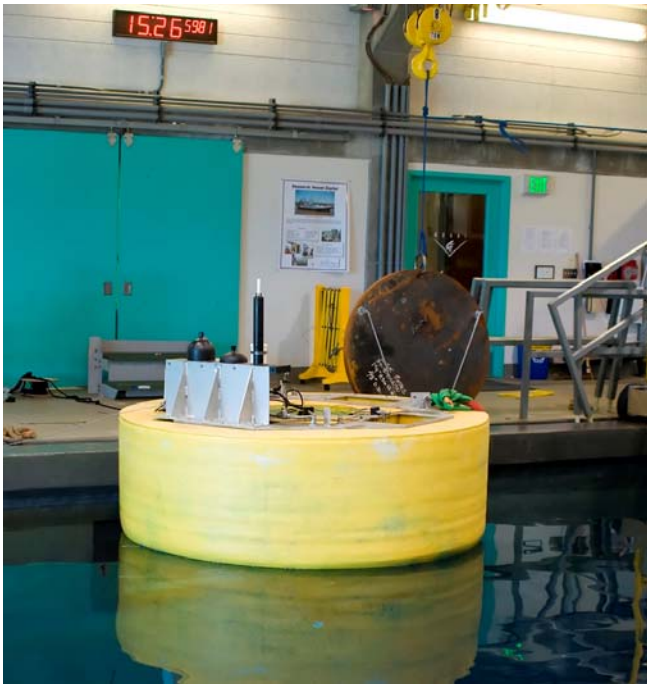

Figure 2: Test buoy in MBARI test tank.

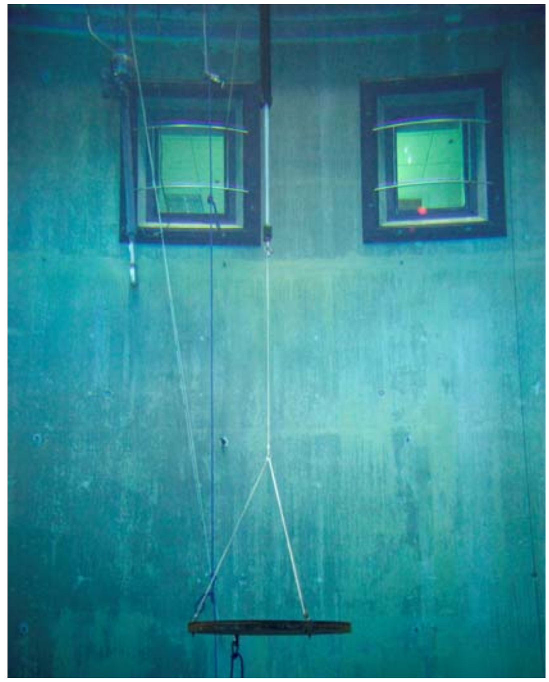

Figure 3: Plate submerged below buoy in test tank, supported by hydraulic ram visible in the top of the photo.

Two tests were performed with this system, the first was a “step-response” test in the MBARI test tank that involved measuring the oscillations of the system that resulted from an initial disturbance. The second set of tests were performed at sea in actual wave conditions. The step-response test is a simplified test of the model in that it does not include any wave exciting forces, that is, the buoy and plate motion is entirely a result of its initial displacement as there are no incoming waves to cause the system to move. This is in contrast to the at-sea tests in which all the motion of the system is due to the incoming waves. The two tests are complementary in that the step-response test includes all frequencies of motion (in theory), but doesn’t exercise the models ability to represent forces on the system due to incoming waves. The at-sea test includes the wave-exciting forces, but only subjects the model to frequencies that are present in the incoming wave-field. The results from these tests are included in the attached technical report.

Attachments

1. MBARI Final Grant Status Report
2. Technical Report: *Time Domain Model Validation Results*

Date: 9/9/2009

Grant Status Report

Month of Aug 2009

Final

Project: 707956
Project Name: EPBuoy:Design Trade Study
Agency Name: DARPA
Prime Contract: HR0011-09-1-0032
Start Date: 2/9/2009 End Date: 9/6/2009

Active?: Y
Project Manager: Hamilton, John A
Project Total Value: $287,829

Account / Pool ID	Name	Total Budget	Ptd Billed	Ytd Billed	Itd Billed	Funds Remaining**	Open PO's w/o Overhd
Details for Grant 707956.00	*EP Buoy:DesignTrade Study*						
6000-000	Direct Labor	106,873.00	11,263.97	102,926.42	102,926.42	3,946.58	0.00
6005-000	Direct Labor - Overtime	0.00	115.44	115.44	115.44	(115.44)	0.00
Total Labor		**106,873.00**	**11,379.41**	**103,041.86**	**103,041.86**	**3,831.14**	**0.00**
001	Fringe - Full	56,643.00	6,031.08	54,612.18	54,612.18	2,030.82	0.00
Total Fringe		**56,643.00**	**6,031.08**	**54,612.18**	**54,612.18**	**2,030.82**	**0.00**
5120-000	OS - External Ship Time	0.00	1,240.00	1,240.00	1,240.00	(1,240.00)	0.00
5130-000	OS - General	20,500.00	0.00	17,676.15	17,676.15	2,823.85	0.00
5200-000	Postage/Shipping	0.00	129.53	129.53	129.53	(129.53)	0.00
5300-000	Supplies - Cmptr/Hdwr	0.00	0.00	914.19	914.19	(914.19)	0.00
5310-000	Supplies - Cmptr/Sftwr	0.00	0.00	2,102.11	2,102.11	(2,102.11)	0.00
5330-000	Non-Capitalized Equipment	0.00	0.00	6,529.99	6,529.99	(6,529.99)	0.00
5360-000	Supplies - General	0.00	0.00	3,628.46	3,628.46	(3,628.46)	0.00
5500-000	Travel - Domestic	6,600.00	0.00	738.42	738.42	5,861.58	0.00
Total Direct Costs		**27,100.00**	**1,369.53**	**32,958.85**	**32,958.85**	**(5,858.85)**	**0.00**
015	Indirect Cost Rate	97,213.00	12,287.96	97,212.58	97,212.58	0.42	0.00
Total Indirects		**97,213.00**	**12,287.96**	**97,212.58**	**97,212.58**	**0.42**	**0.00**
Totals for Grant 707956.00 EP Buoy:DesignTrade Study		*287,829.00*	*31,067.98*	*287,825.47*	*287,825.47*	*3.53*	*0.00*
Grant Totals		**287,829.00**	**31,067.98**	**287,825.47**	**287,825.47**	**3.53**	**0.00**

** Balance Excludes Open PO's

Time Domain Model Validation Results

Introduction

In order to analyze the behavior of various wave-energy extraction devices, a general purpose numerical model has been developed that can be configured to model different design concepts. Because this model makes a number of simplifying assumptions, it's important to validate the results of a typical system against experimental results. This report outlines and compares the numerical and experimental results for a simple case of a floating buoy that supports a submerged heavy body 20 meters below the buoy. The two bodies are connected by a hydraulic ram system that behaves like a damped spring element. To validate the model, this system was deployed in Monterey Bay on August 10th and 11th, 2009. The sea state during the tests and the resulting motions of the system were measured and recorded. Subsequent to this experiment the numerical model was run using the sea state from the test days as an input and the results were compared. In addition to the at-sea testing, a step response test of the system was performed in the MBARI test-tank, which consisted of dropping the buoy from a small elevation and measuring the resulting tension and elongation step response.

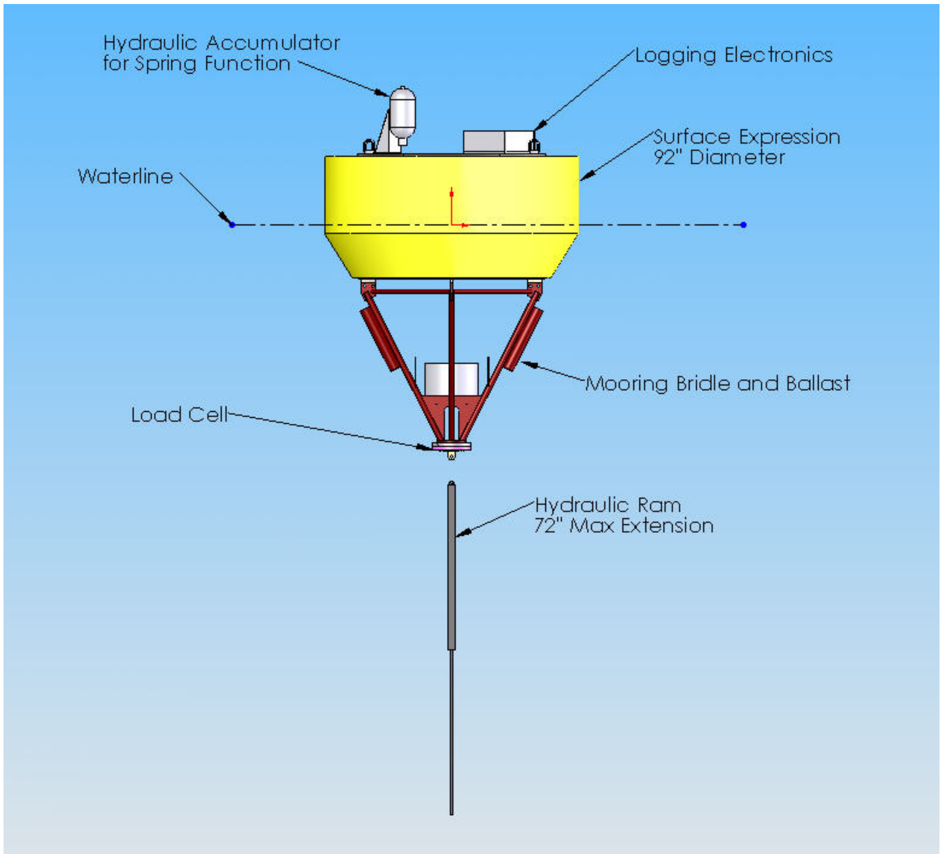

Figure 1: Surface expression and hydraulic cylinder acting as spring/damper system. Flat plate or sphere is connected and submerged at a depth of 20 meters.

Experimental Set-Up

The experimental set-up consists of a cylindrical surface float and a submerged element that is connected by a hydraulic ram system that behaves as a spring element. Figure 1 shows the surface-buoy configuration. Two different submerged elements were used, a 48" diameter flat plate and a 28" diameter sphere. These two elements were used to provide some variation in the device configuration; the numerical model was run in both configurations as well. The details of the two configurations that were tested are outlined below:

Configuration I

Floating Body: MOOS Buoy

- Total Mass: 2600 lbs (1179.34 kg)
  (includes Hydraulic ram, Instruments, Accumulators, Heave Sensor and Bridle assembly)
- Waterline: 4 inches (0.1016 m) above Chine (Location of Origin)
- Center of Gravity: [0, 0, -0.63m]
- Center of Buoyancy: [0, 0, -0.26m]
- Displacement: 1.64 m^3
- Moment of Inertia about Origin
  I_{xx} = 1998.19 kg m^2
  I_{yy} = 1947.66 kg m^2
  I_{zz} = 466.13 kg m^2
- Tether Point of Attachment: 2.0 m below chine (2.09 m below waterline)
- Tether Length = 3.0m (test-tank tests), 20.0m (at-sea tests)

Submerged Body: Flat Circular Plate

- Total Mass: 1297 lbs (588.31 kg)
- Radius: 2 ft (0.6096 m)
- Thickness: 2.5 inches (0.0635m)
- Displacement: 0.074133 m^3
- Center of Gravity: [0, 0, 0]
- Center of Buoyancy: [0, 0, 0]
- Moment of Inertia about Origin
  I_{xx} = 55.22 kg.m^2
  I_{yy} = 55.26 kg.m^2
  I_{zz} = 110.08 kg.m^2
- Tether Point of Attachment = (54.25 inches) 1.37795 m above CG of plate

Configuration II

Floating Body: MOOS Buoy

- Total Mass: 2600 lbs (1179.34 kg)
  (includes Hydraulic ram, Instruments, Accumulators, Heave Sensor and Bridle assembly)
- Waterline: 2.25 inches (5.715 cm) above Chine
- Center of Gravity: [0, 0, -0.63m]
- Center of Buoyancy: [0, 0, -0.29 m]
- Displacement: 1.475 m^3

- Moment of Inertia about Origin
  I_{xx} = 1998.19 kg.m ^{2}
  I_{yy} = 1947.66 kg.m ^{2}
  I_{zz} = 466.13 kg.m ^{2}
- Tether Point of Attachment: 2.0 m below chine (2.09 m below waterline)
- Length of tether: 20m (at-sea tests)

Submerged Body No. 2: Solid Sphere

- Total Mass: 1175 lbs (532.97 kg)
- Radius: 14 inches (0.3556 m)
- Displacement: 0.0188354 m ^{3}
- Center of Gravity: [0, 0, 0]
- Center of Buoyancy: [0, 0, 0]
- Moment of Inertia about Origin
  I_{xx} = 26.958 kg.m ^{2}
  I_{yy} = 26.958 kg.m ^{2}
  I_{zz} = 26.958 kg.m ^{2}
- Tether Point of Attachment = (14 inches) 0.3556 m above CG of sphere.

Hydraulic System Description

The spring/damper system is constructed from industrial hydraulic components, a 72" long linear ram provides compliance and is plumbed to a system of accumulators and valves that provides a spring effect (force proportional to displacement) and a damping effect (force proportional to velocity). Because it is difficult to construct a perfectly linear spring and damper system from these hydraulic components, the actual characteristics of the spring/damper system was measured for inclusion in the numerical model. Figure 2 depicts a schematic representation of the hydraulic system designed and used in the validation experiment. Three accumulators of capacities 1 quart, half gallon and one gallon with precharges 50, 200, 500 psi respectively, provide the required spring force. A pressure sensor (P1) was connected to measure the pressure in the system which is proportional to the tension in the tether.

The spring force in the system is a result of the gas being compressed in the accumulators as the piston rod extends, this is not a linear phenomenon but the three accumulators in parallel approximate a linear spring as shown in the measured force versus elongation results (Figure 3). This measured spring relationship is what is used in the numerical model.

The measured damping force present in the experimental set-up is shown in figure 4, this highly nonlinear damping relationship is approximated for purposes of inclusion in the model in terms of elongation rate '*v*' as

$$Fd = \frac{\Delta F}{2}\left(1-\exp(-\alpha v)\right) sign(v) \qquad (3)$$

where

ΔF = mean damping force in N/(m/s)

α = velocity slope coefficient (1/(m/s))

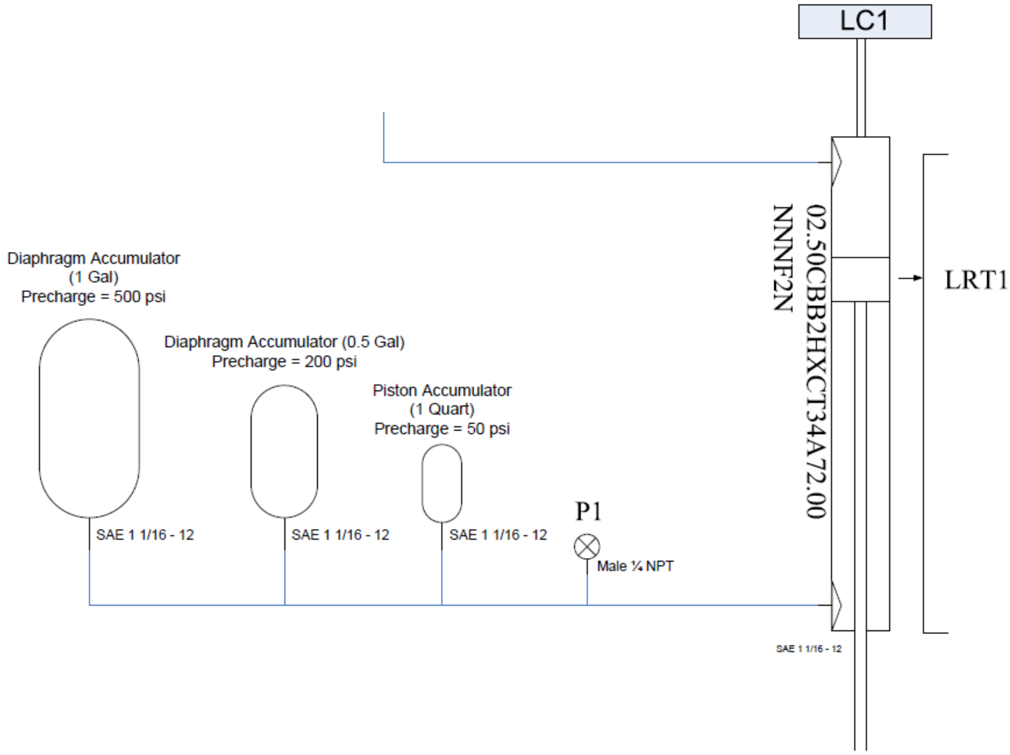

Figure 2. Schematic drawing of the hydraulic components showing the ram, the accumulator system, load cell (LC1), pressure sensor (P1) and potentiometer (LRT1).

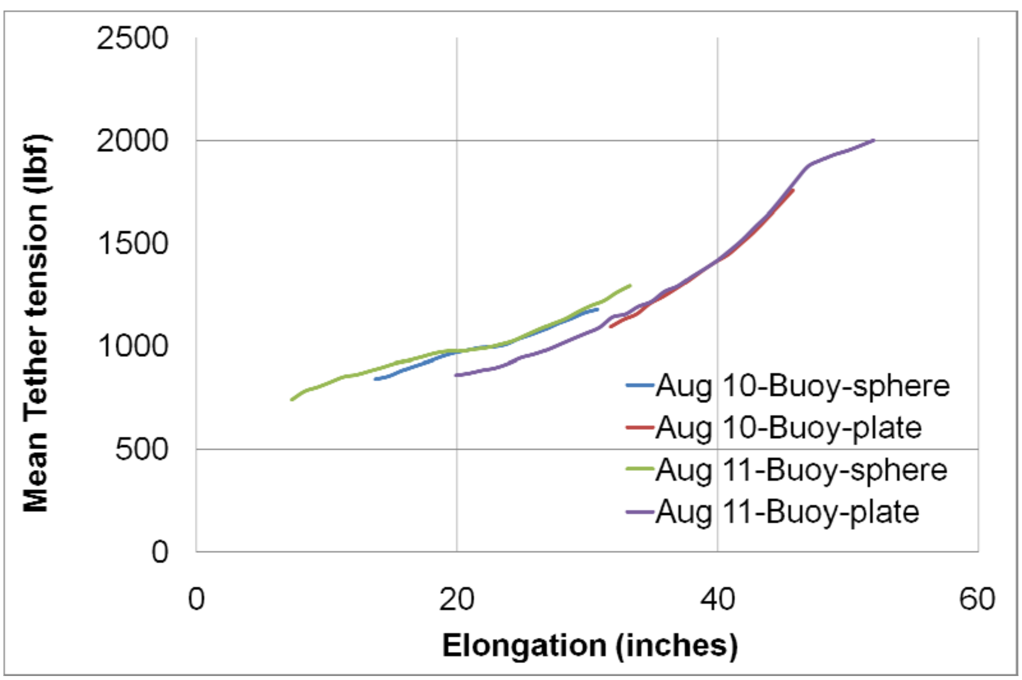

Figure 3. Experimental measurements of mean tether tension as a function of tether elongation.

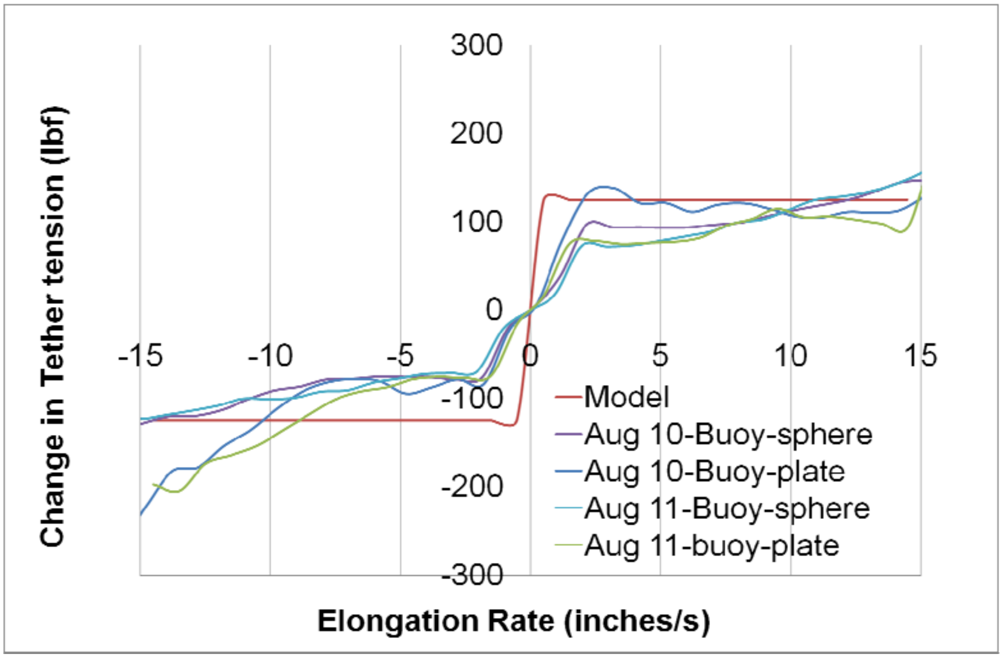

Figure 4. Variation of tether tension about the mean value in Figure 3 measured at variable tether elongation rates.

To measure the actual tensions in the system, a load cell was bolted to the lower end of the bridle to measure the tension force acting on the tether connecting the submerged element to the surface float (see figure 1). The stroke of the hydraulic ram and the resulting tether elongation was measured by a built-in potentiometer in the hydraulic ram.

The incoming wave field was measured by a nearby wave-measurement buoy. A significant wave height of 1.0 m at a peak period of 7.2 seconds were recorded on August 10th near the experimental site whereas the wave conditions were considerably milder on August 11th with the significant wave height and peak period values being 0.7 m and 8 seconds respectively. The wave spectral plots appear in figures 7 to 10. Field experimental results are sub-divided into four datasets for the ease of understanding, namely, Buoy-plate August 10th, Buoy-plate August 11th, Buoy-sphere August 10th and Buoy-sphere August 11th.

All quantities of tension, pressure and elongation were logged on-board the buoy at 100Hz for later analysis.

Additional Calibration Information

Figure 5 shows the calibration chart of the potentiometer built into the hydraulic ram used to measure the elongation of the tether connecting the surface buoy to the submerged element. Voltage changes nearly linearly with elongation. An extension of approximately 15 inches changes the measured voltage by 1 volt.

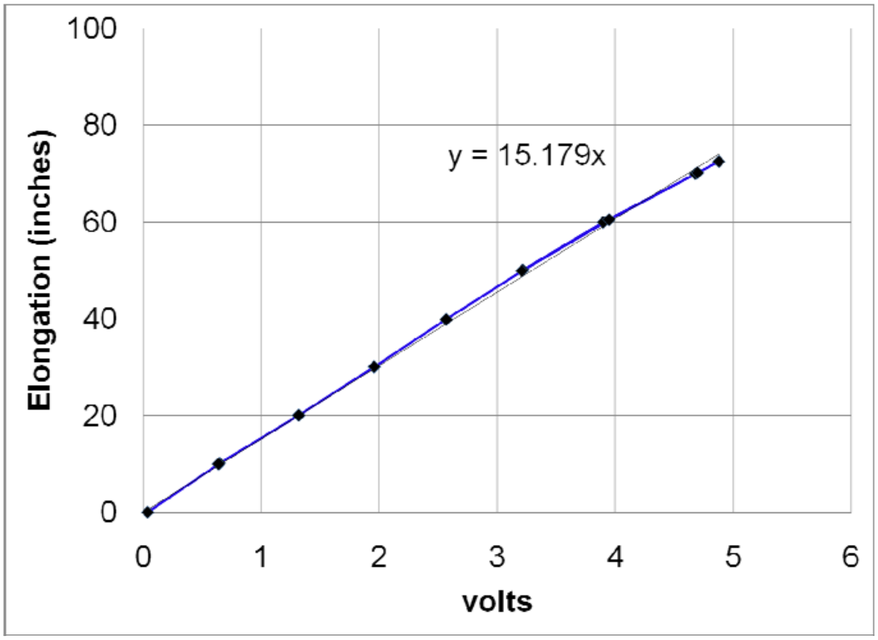

Figure 5. Experimental measurement of potentiometer calibration

Numerical Model

The numerical model consists of an equation of motion solver that computes the resulting motion in three dimensions of a collection of floating and submerged bodies that are subject to external forcing acting on the various bodies that make up the system. The forces acting on the surface buoy include weight, hydrostatic force, wave-exciting force, wave radiation force, skin-friction and pressure drag and the tether tension. The submerged element (sphere/plate) is forced by weight, hydrostatic force, skin-friction and pressure drag and the tether tension. The hydrodynamic frequency-domain coefficients were calculated by using WAMIT Version 6.4. WAMIT is a radiation/diffraction code developed for the analysis of the interaction of surface waves with floating bodies. A separate utility was used to evaluate time-domain impulse response functions from the outputs of WAMIT.

Results and Discussion

Two types of tests were performed for the purpose of validating the numerical model. A step response test was conducted in the MBARI test tank and two days of testing was performed at sea to measure the systems response to ocean waves.

Step Response test

The step response experiment was conducted in the MBARI test tank on the Buoy-plate system, the buoy was lifted to a height of 12 inches and released. Experimental and modeling results of the step response test are presented in figure 6. There is excellent agreement in the phase of the motion response and tether elongation but the magnitude of tether tension is underestimated in the modeled results. This discrepancy is most likely due to the fact that the elongation rates are very high step response tests and the modeled results fails to accurately simulate the damping forces in the ram at a very high rate of tether elongation. The tension results show a high frequency disturbance at the two and four second marks. Based on observation of video of the tests, this interaction appears to be the effect of waves reflecting from the walls of the test tank.

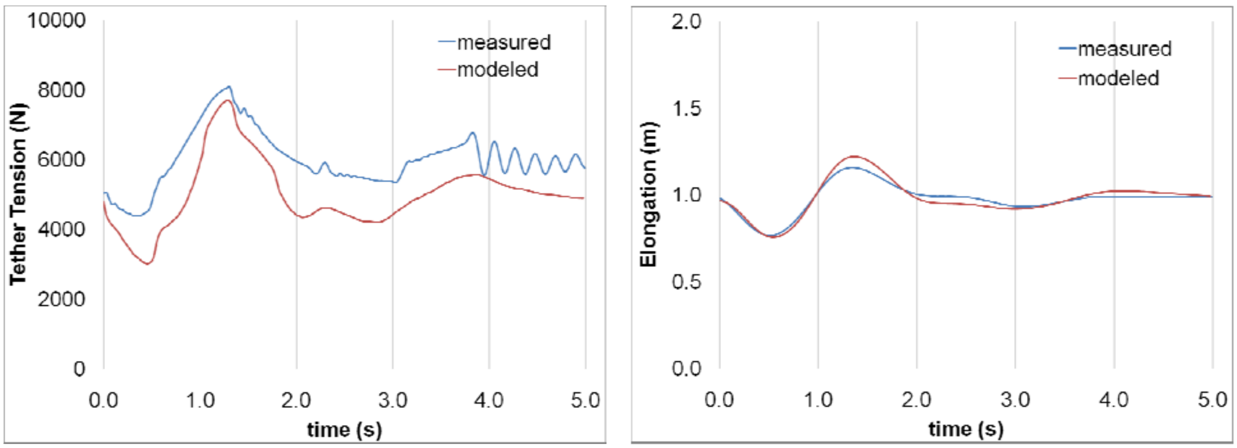

Figure 6. Experimental measurements and model generated values of tether tension and elongation during the step response test.

Monterey Bay Field experiment

Experimental measurements and modeling results of the systems tension and elongation response are plotted in figures 7 to 10 along with concurrent measurements of wave time history and spectra. Comparisons were made for the purposes of validating the numerical modeling results against the experimental observations of tether tension. To accurately model the hydraulic ram dynamics, the experimental observations of spring and damping force as a function of elongation and elongation rate respectively were incorporated into the model. Laboratory experiments were also conducted for confirming the spring and damping forces observed in the field experiments. At small elongation rates, the hydraulic ram dynamics was well understood. At rates exceeding 10 inches/s, there was some amount of uncertainty in the dynamic behavior of the hydraulic ram.

Comparison of experimental observations with numerical modeling results indicates reasonably good agreement. The simplified numerical model captures the buoy-plate and the buoy-sphere system hydrodynamics fairly well as illustrated in figures 7 to 10. In all cases the elongation and tension spectra have a pronounced peak at a frequency that is higher than the peak of the incoming wave spectra, this appears to be related to the natural frequency of the tether system.

The motion of the submerged body attached to the hydraulic ram can be analyzed as a single degree of freedom system oscillating along the heave direction. In this case the natural frequency of the hydraulic cylinder motion is given by

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m+a}} \qquad (1)$$

where f_n = natural frequency in Hertz
k = Spring stiffness (N/m)
m = mass of the submerged object (kg)
a = added mass of the submerged object (kg)

Table 1 shows the expected natural frequency of the two configurations based upon linearized estimates of spring stiffness based upon the measured values of force versus elongation shown in figure 3.

Submerged Body	*k (N/m)*	*m (kg)*	*a (kg)*	*Tn (s)*	*fn (Hz)*
Circular Plate	4879.6	588.3	632.2	3.14	0.32
Sphere	2065.0	533.0	193.1	3.73	0.27

Table 1. Linearized hydraulic ram oscillation characteristics.

Results show that a near-zero frequency response exists when the wave exciting force is not high enough to overcome the frictional force which causes the ram to get stuck at one particular location for several seconds. For a buoy-sphere system, the variation of tether tension due to the oscillatory wave motion is about half of that of the buoy-plate system. Lower tension variation causes several instances of mechanical stiction to occur. On the other hand, tether elongation measurements for the buoy-plate system show very little stiction. The numerical model is not able to replicate the stiction mechanism observed in experiments and therefore, the near-zero frequency response is absent in the modeling results. Instead, it is represented as a low amplitude time variation in the plot of elongation with time.

The hydrodynamic damping force acting on the sphere is much lower in magnitude as compared to that of a flat plate. As a result, it takes considerably longer for the sphere to come to rest at the equilibrium position. The rate of tether elongation remains linear for small variations in tether tension and tends to become constant at higher values. Due to low damping, it does not become non-linear. For the system with a flat plate as the submerged element, high damping values tend to introduce non-linearity for large variations in tether tension. The non-linear frequency response is observed in experimental measurements at frequencies higher than the wave excitation frequencies.

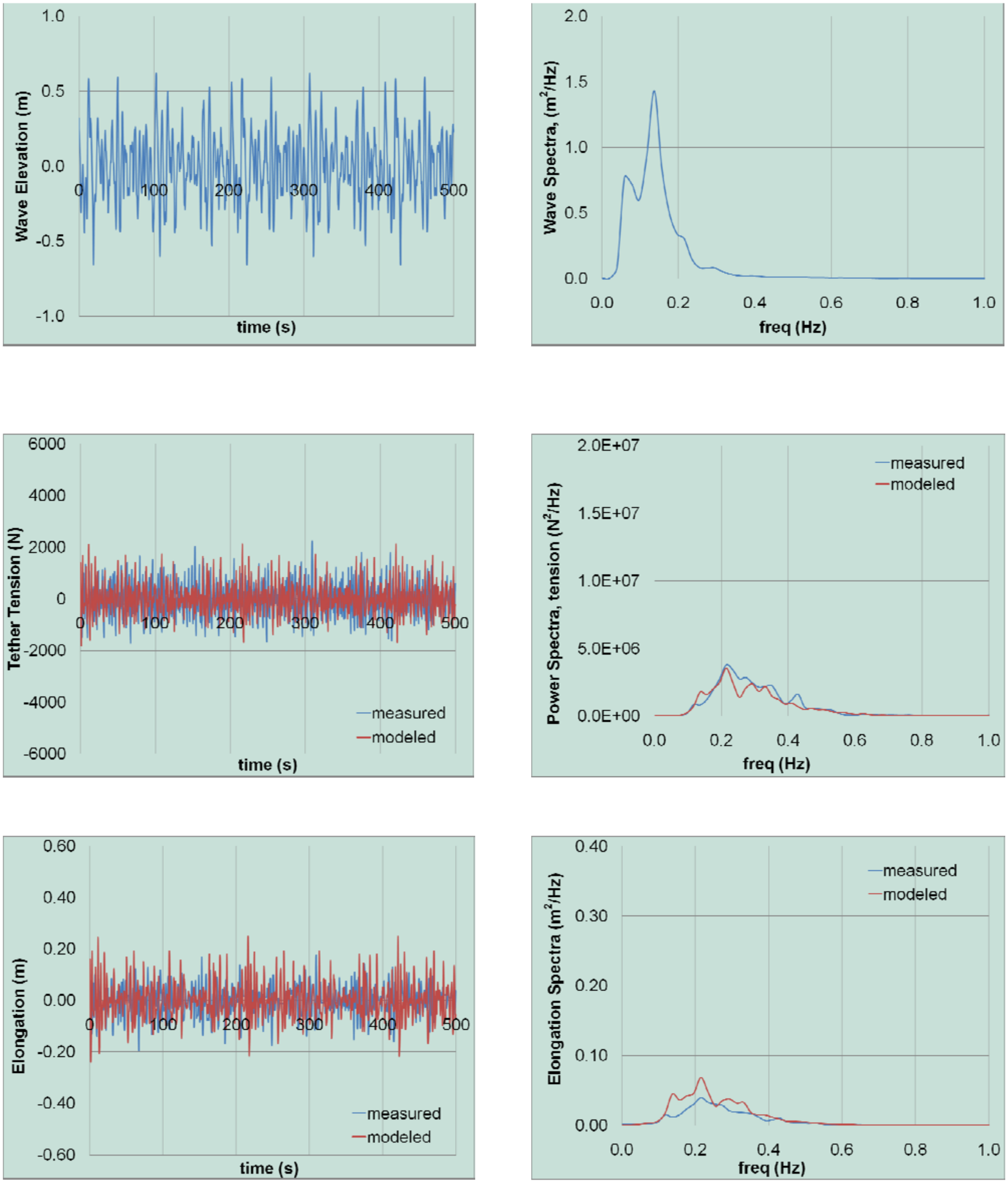

Figure 7. Time history and corresponding spectra of wave elevation, measured and modeled tether tension and elongation. (Buoy-plate Aug 11, 2009)

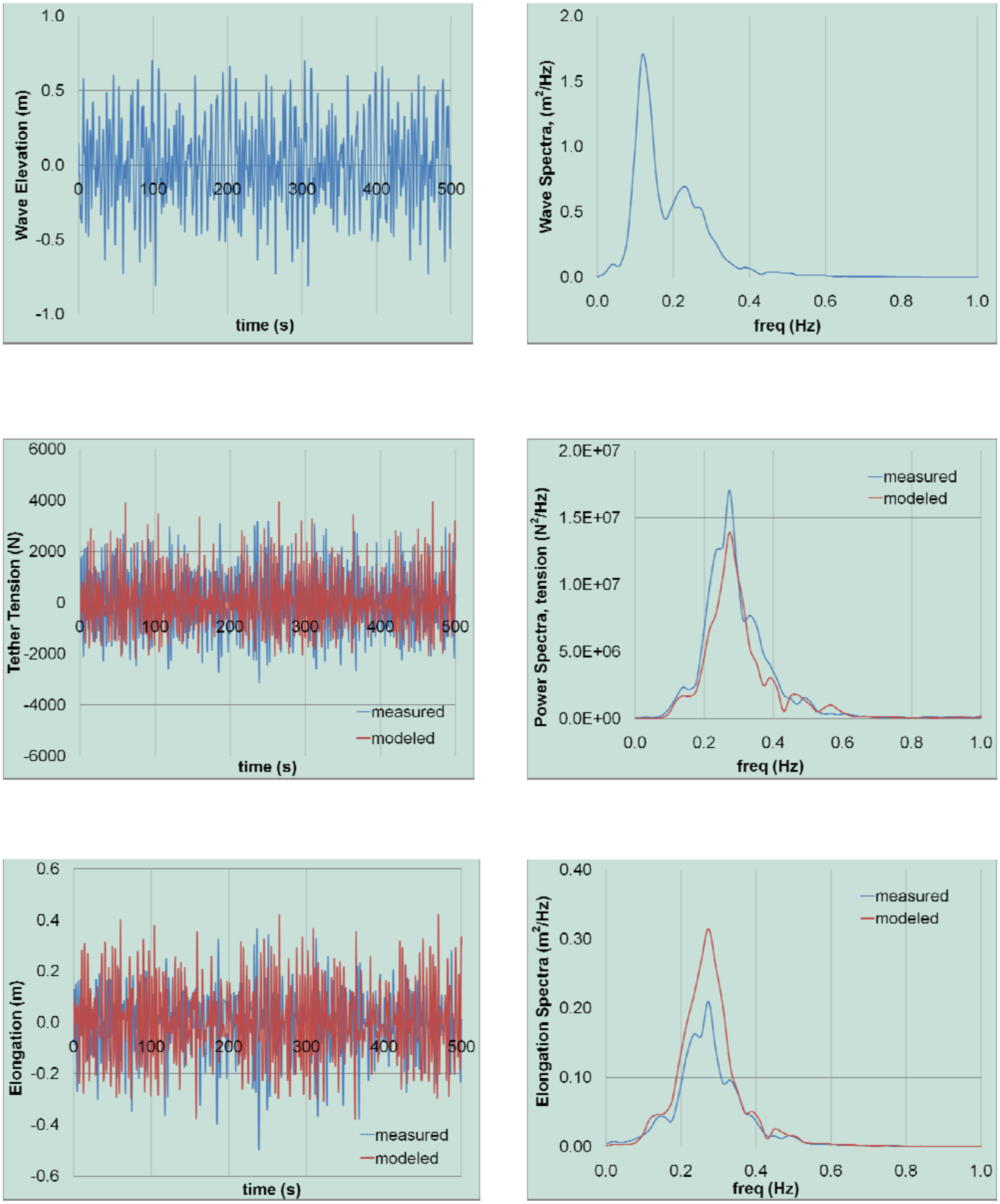

Figure 8. Time history and corresponding spectra of wave elevation, measured and modeled tether tension and elongation. (Buoy-plate Aug 10, 2009)

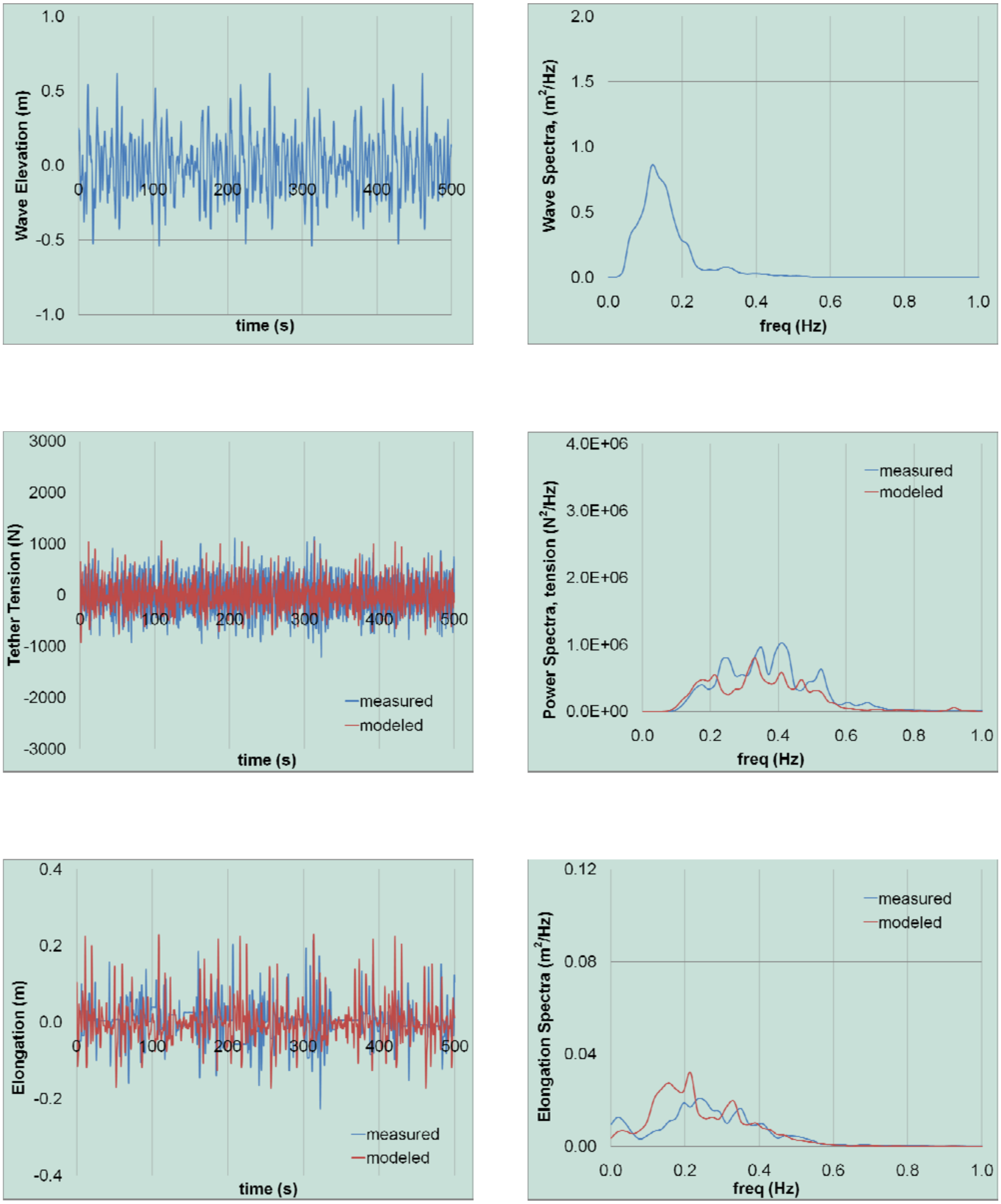

Figure 9. Time history and corresponding spectra of wave elevation, measured and modeled tether tension and elongation. (Buoy-sphere Aug 11, 2009)

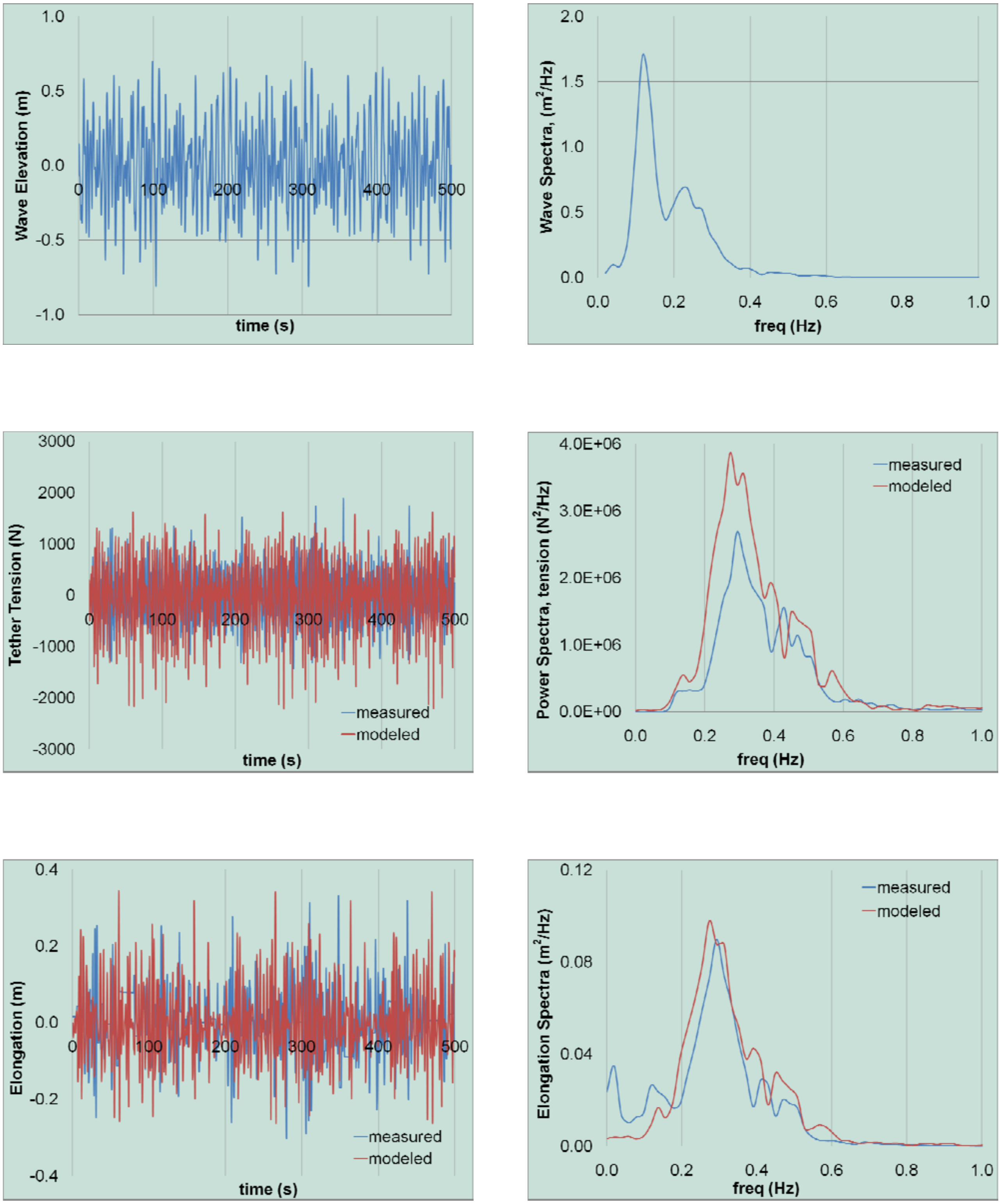

Figure 10. Time history and corresponding spectra of wave elevation, measured and modeled tether tension and elongation. (Buoy-sphere Aug 10, 2009