SAND2016-1727C
Proceedings of the 4th Marine Energy Technology Symposium
METS2016
April 25-27, 2016, Washington, DC

WEC AND SUPPORT BRIDGE CONTROL STRUCTURAL DYNAMIC INTERACTION ANALYSIS

David Wilson*
Sandia National Laboratories
Albuquerque, NM, USA

Giorgio Bacelli
Sandia National Laboratories
Albuquerque, NM, USA

Ryan G. Coe
Sandia National Laboratories
Albuquerque, NM, USA

Rush D. Robinett III
Michigan Technological University
Houghton, MI, USA

Gareth Thomas
ATA Engineering, Inc.
San Diego, CA, USA

Daniel Linehan
ATA Engineering, Inc.
San Diego, CA, USA

David Newborn
Naval Surface Warfare Center Carderock Division
Bethesda, MD , USA

Miguel Quintero
Naval Surface Warfare Center Carderock Division
Bethesda, MD , USA

ABSTRACT

Experimental testing is a critical step in the development of models describing the behavior of a system. The objective of the experimental testing presented in this document is to obtain models for the design of control systems for a Wave Energy Converter (WEC). The particular WEC considered here is a heaving point absorber composed of a floating buoy (see Fig. 1) connected to a support structure through a linear actuator. The support structure is then attached to the side of a bridge (see Fig. 2). The testing will be conducted at the Maneuverability and Seakeeping (MASK) basin located at the Naval Surface Warfare Center Carderock Division (NSWCCD), Bethesda, MD. The actuator applies a force between the floating body and the support structure in order to absorb power from waves. The simplest control strategy that is commonly used for power absorption is linear damping, where the force applied by the actuator is proportional to the velocity of the buoy; in practice, this constitutes a very simple static feedback (no dynamics in the feedback loop):

$$F_u = -Bv \tag{1}$$

where F_u is the actuator's force, v is the velocity of the buoy and B is the damping coefficient.

The support structure cannot be assumed to behave as a fixed reference, thus the actuator connects two oscillating structures (the bridge/support structure and the WEC). Both a modal analysis and experimental testing have been conducted by ATA Engineering on the bridge in order to study the dynamical response of the bridge. Figure 5 depicts the frequency response function (FRF), and it can be seen that the lowest two modes of interest (vertical bending and torsional) are very close to the range of frequencies that will be used for the testing of wave-body interactions by means of waves in the range of $0.4 - 1.0$ Hz. The objective of this paper is to analyze the potential adverse effects of having a feedback control system applied between these two structures that have close resonance frequencies, and to propose a control design solution for the mitigation of these interactions.

BRIDGE STRUCTURAL DYNAMICS EVALUATION

The WEC system will be installed at the NSWCCD Carderock wave pond MASK basin facility. The WEC will be attached to the bridge that spans the basin, as shown in Fig. 2. The WEC system will generate loads from wave movement and there is the potential that the bridge may become excited during the WEC evaluation. A detailed discussion of the modal test of the bridge, subsequent analyis approach, and the development of a simpli-

*Corresponding Author: dwilso@sandia.gov

fied bridge model are given in the final report by ATA [1]. The highlights from this report are discussed here with respect to the Control-Structure-Interaction (CSI) between the bridge and the WEC system.

FIGURE 1: WEC system heaving point absorber composed of a floating buoy.

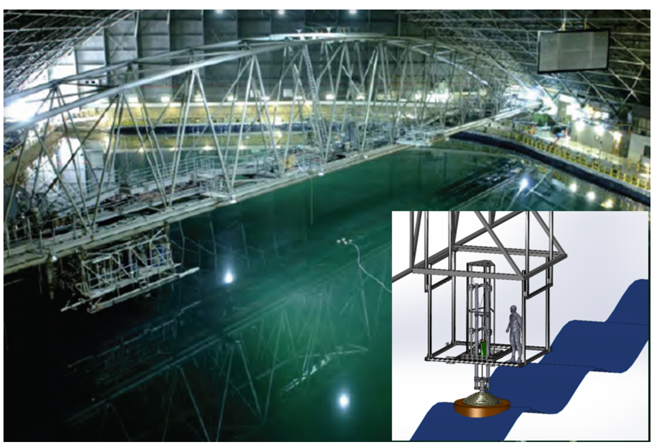

FIGURE 2: WEC system converts wave motion to electrical energy through a linear generator system.

The details of the specific tests and models are given in [1]. The test resulted in two frequencies of interest. The first vertical bending mode and the bridge first torsion mode and are shown visually in Figs. 3 and 4, respectively. A bridge FEM was required to meet the objectives of this project because modal testing alone would not be able to reflect the final bridge configuration following the final WEC hardware installation. This complete model was then subjected to a forced response analysis in which a unit sinusoidal load was applied to the interface frame in a frequency sweep from 0.1 Hz to 4 Hz. The load point was offset from the middle of the 118” x 128” cantilevered bay of the WEC interface frame in accordance with the WEC model provided by SNL. The dynamic analysis procedure known as mode acceleration was used for this analysis. The resulting displacement response at the loaded node is shown in Fig. 5.

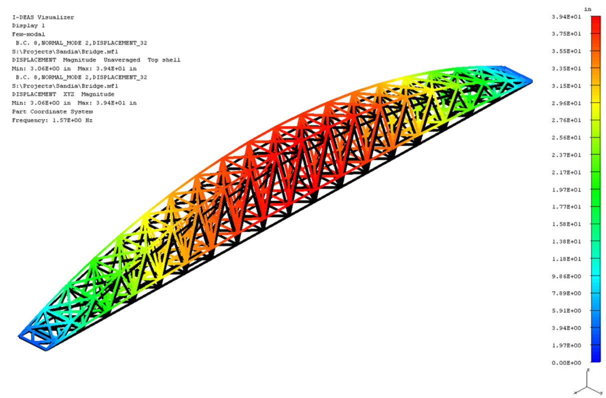

FIGURE 3: First vertical bending mode of bridge at a frequency of 1.57 Hz with 0.27% estimated damping.

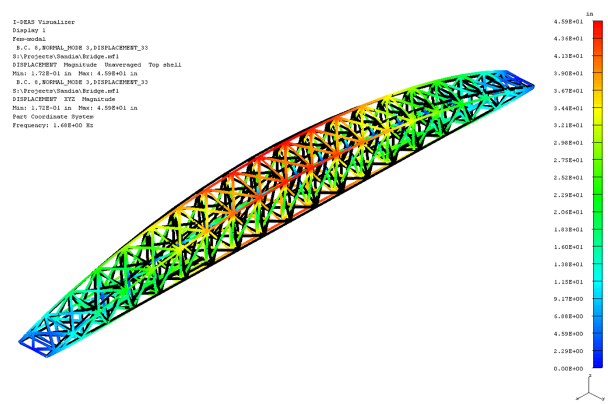

FIGURE 4: First torsional mode of bridge at a frequency of 1.68 Hz with 0.37% estimated damping.

Of special interest in this plot is the fact that there is almost no dynamic amplification of the excitation force below 1 Hz, as indicated by the horizontal line between 0 and 1 Hz. In other words, the structure is expected to behave in a quasi-static fashion in this frequency range. This should be of particular rele-

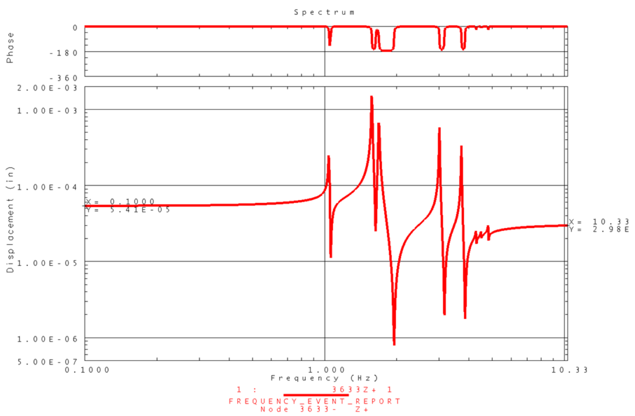

FIGURE 5: Driving point FRF for the WEC frame (based on a mode acceleration analysis).

vance to control system analysts interested in how the WEC may interact with the bridge.

Low-level impact loading modal testing was performed on the sea-keeping basin bridge at NSWCCD Carderock in Potomac, Maryland. This test identified two important modes of vibration in the 0 to 2 Hz frequency range of interest. These modes consist of a bending mode at 1.56 Hz and a torsional mode at 1.69 Hz. These modes needed to be quantified because it is believed that they may affect the dynamic performance of a WEC device that is to be mounted to this bridge for testing.

A finite element model of the bridge was constructed using 1-D beam elements throughout. This model was correlated with the modal test data by tuning the mass and stiffnesses of deck members. These variations confirm that the behavior of the bridge is more complex than that implied by the initial simple model that was based on the primary structure described in design drawings. The tuned analytical model provided very good agreement with the frequencies of the two important modes of vibration.

The finite element model was used to characterize the residual flexibility of the system and to show its importance in the dynamic performance of the bridge at low frequency.

CONTROL STRUCTURE INTERACTION (CSI)

To address potential control structure interaction between the WEC system and the supporting bridge several techniques exist from the aerospace large space structure area that address precision pointing and slewing while suppressing vibrations of the structure [2,3]. The dynamic modeling of complex structural systems can be accomplished with finite element methods. A simple single actuator (input) that is located at a nodal DOF i, and sensed (output) from a nodal DOF j location can be represented in a transfer function relationship as [2]

$$\frac{x_j(s)}{f_i(s)} = \frac{1}{Ms^2} + \sum_{k=R+1}^{m} \frac{\phi_{ik}\phi_{jk}}{s^2 + 2\zeta_k\omega_k s + \omega_k^2} \qquad (2)$$

where x_j, f_i are the nodal displacements and forces, ω_k, ϕ_k are the m natural frequencies and mode shapes of vibration (normalized to unit mass), ζ_k is the damping factor, and M is the effective rigid-body mass of the plant with R rigid-body modes.

The transfer function can be merged into one common transfer function [2] where the modal participation coefficient of mode k can be defined as

$$\alpha_k = 1 + M\phi_{ik}\phi_{jk} \qquad (3)$$

where through the definition of α_k several interesting characteristics that are useful for this analysis are discussed in [2]. For a lightly damped structure it is important to review the flexible modes which are identified by two parameters, i) the modal resonance frequency, ω_k, and the modal participation coefficient α_k The pole-zero pattern on the jω axis is important. Three possible combinations exists; 1) appendage mode $\alpha_k > 1$, ii) in-the-loop minimum phase mode $0 < \alpha_k < 1$, and iii) in-the-loop nonminimum phase mode $\alpha_k < 0$. Figure 6 shows a block diagram representing the two bridge modes (N=2) interacting with the WEC resistive controller. A preliminary analysis of all three types of combinations were reviewed and the last two, in-the-loop minimum and nonminimum phase modes may cause potential modal interaction and excitations during WEC performance operations. Further details will be discussed in the final analysis.

As one possible solution, a shaping filter can be designed to avoid the bridge resonant frequencies. For our preliminary analysis a simple notch filter is placed in the compensator to reject the resonance of interest.

RESULTS

The preliminary results reported here include an in-the-loop minimum phase mode for $\alpha_1 = 0.7$ associated with the first vertical bending mode. The first torsional mode was set to $\alpha_2 = 2.0$ or an appendage mode. Actual values from the calibrated finite-element models and FRF test will be incorporated for the final analysis. The WEC device resonant frequency is $f_n = 0.625$ Hz. The excitation force was set to be driven at the resonant frequency of the device f_n. Numerical simulations using Matlab/Simulink were performed for two cases. The first case is without any compensation where the results for the device heave velocity and flex modes one and two are shown in Figs. 7-9. The modes and responses begin to grow in an unstable manner. For the second case the shaping filter (notch filter) is designed at

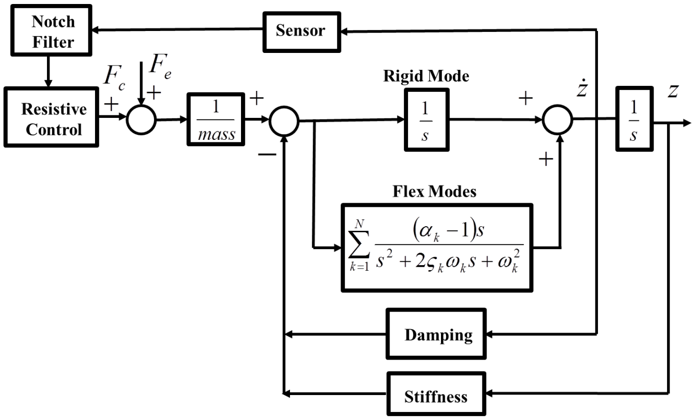

FIGURE 6: WEC servo loop block diagram with flexible modes and bridge compensation.

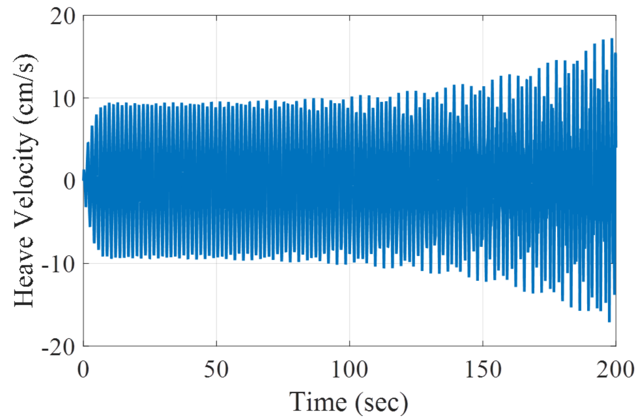

FIGURE 7: CSI simulation results heave velocity unstable mode.

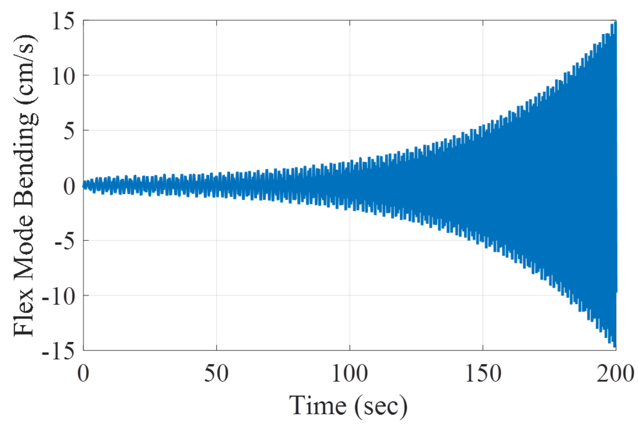

FIGURE 8: CSI simulation results flex mode bending unstable mode.

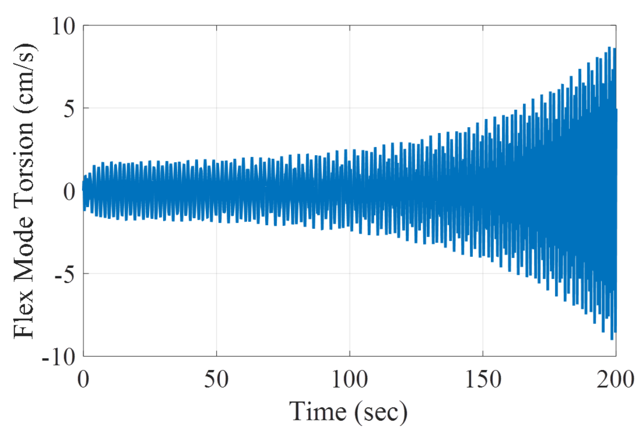

FIGURE 9: CSI simulation results flex mode torsional unstable mode.

the first vertical frequency mode resonance. The modes and responses are shown again in Figs. 10-12 which resulted in stable responses.

CONCLUSIONS

The goal of this study is to identify potential CSI problems and potential solutions to minimize interactions during the WEC peformance evaluations. Structural dynamic analysis results were reviewed and a potential CSI solution path was identified and evaluated. Further developments will be included for the final analysis.

ACKNOWLEDGMENT

This work was funded by the U.S. Department of Energy's Wind and Water Power Technologies Office. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

REFERENCES

[1] Linehan, D. and Thomas, G.R., *Test Analysis Evaluation of MASK Basin Bridge Structural Dynamics for Advanced WEC Controls Hardware*, Final Report, ATA Engineering, Inc., San Diego, Ca., Jan. 2016.

[2] Spanos, J.T., *Control-Structure Interaction in Precision Pointing Servo Loops*, J. Guidance, Vol.12, No.2, 1989.

[3] Quinn, R.D. and Yunis, I.S., *Control/Structure Interactions of Space Station Solar Dynamic Modules*, Journal of Guidance, Control, and Dynamics, Vol. 16, No. 4, July-August 1993.

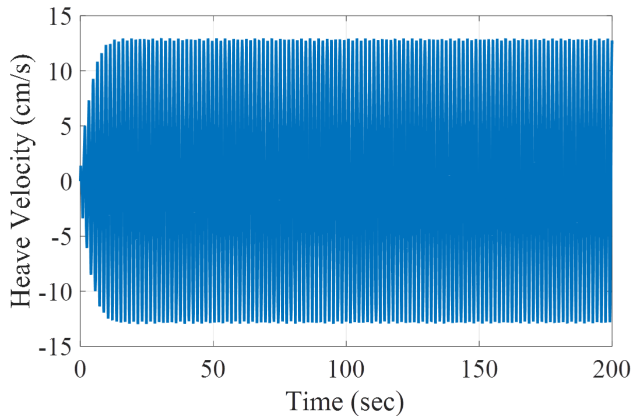

FIGURE 10: CSI simulation results heave velocity stable mode.

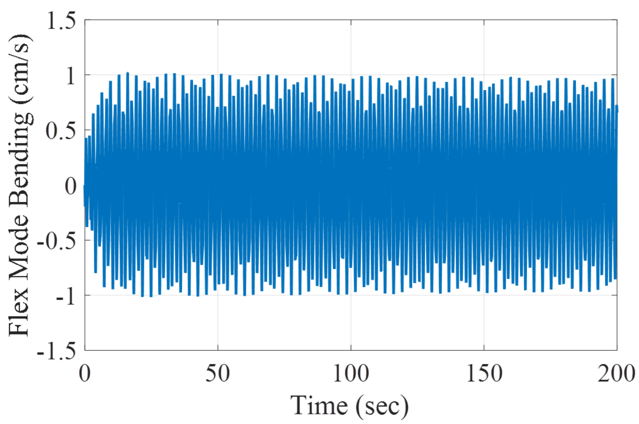

FIGURE 11: CSI simulation results flex mode bending stable mode.

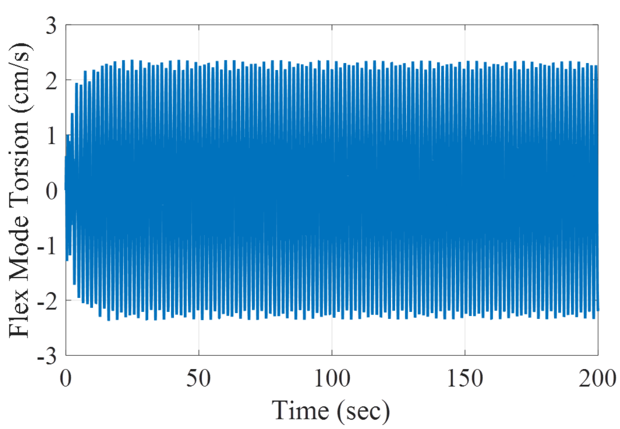

FIGURE 12: CSI simulation results flex mode torsional stable mode.