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Tool for Distributed Pressure Time-Histories of Marine Structures: Verification and Case Study With a WEC

Carlos Michelen*
Sandia National
Laboratories
Albuquerque, NM, USA

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

Yi-Hsiang Yu
National Renewable Energy
Laboratory
Boulder, CO, USA

Qi Wang
National Renewable Energy
Laboratory
Boulder, CO, USA

*Corresponding author: cmichel@sandia.gov

ABSTRACT

In this paper we describe the theory and code implementation of a tool to obtain the time-dependent pressure distribution on a marine structure using the results from a boundary element method code (BEM). Here, we present a case study of a floating wave energy converter (WEC) in regular waves. The results are verified by comparison with open-source codes and then used to run a structural simulation (finite element analysis) to showcase a possible application.

1. INTRODUCTION

The wave energy industry relies heavily on low and mid-fidelity hydrodynamic codes for simulation and design of wave energy converters (WEC). These codes have proven to be of acceptable accuracy, at least on the early design stages, and require orders of magnitude less time to run than high-fidelity Navier-Stokes based computational fluid dynamics codes. Most of these low and mid-fidelity codes are based on solving the time-domain Cummins equation[1], using coefficients obtained from a boundary element method (BEM) code. The coefficients used, and the forces calculated, are for the entire body as a whole.

These global forces and moments are adequate for predicting the device dynamics, but are not of much use in analyzing the structural response of a device. One approach to obtain the distributed pressure loads required for in-depth structural analysis is to use the high-fidelity fluid codes; however the computational cost of these codes makes them impractical for much of the design process. This paper introduces a tool for obtaining pressure distribution time-histories from BEM output and the body motion solution provided by low and mid-fidelity models. This will be an open-source, mid-fidelity, fast-running tool for structural analysis of WECs at the early design stages.

2. OPEN-SOURCE FRAMEWORK

This tool will not be a stand-alone code, rather it will be integrated into BEMIO [2]. BEMIO is a Python-based open-source code for parsing and post-processing BEM results and meshes from different codes into a common format. BEMIO is developed by the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL), and is distributed through GitHub. In the spirit of open-source code development, NEMOH [3] was chosen as the first BEM code with which to implement this pressure-distribution functionality. NEMOH is a free and open source boundary element method code developed at the Ecole Central de Nantes.

3. DEVICE GEOMETRY

The geometry used for this case-study and verification is a 1:17 scale experimental device [4]. It consists of a single floating buoy with wedged profile, as shown in Figure 1. In order to make the problem simpler, the as-built structures were not used. Instead, the WEC was assumed solid and the density was chosen to match the correct mass properties.

4. IMPLEMENTATION AND VERIFICATION

The code is written in Python and implemented within BEMIO. Prior to using this tool, NEMOH must be run with the '*Save pressure on body surface (1 for yes)*' flag ON in the Nemoh.cal file. This will output the cell-by-cell complex pressure coefficients. The radiation pres-

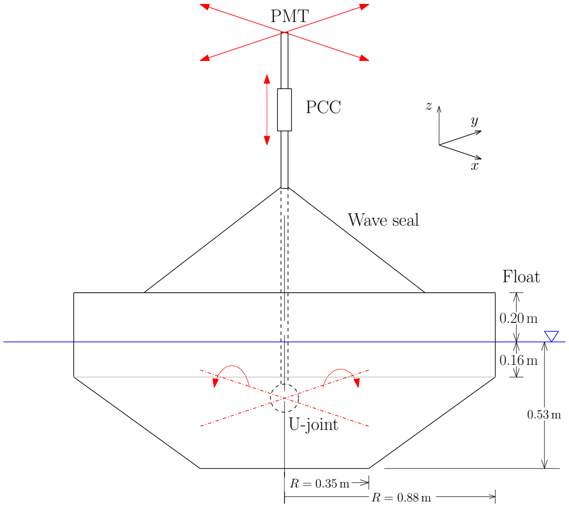

Figure 1: Device geometry [4].

sure coefficients are calculated for each frequency and degree of freedom combination, and the diffraction pressure coefficients are calculated for each frequency and wave direction combination.

The pressure distribution time-history tool is implemented to work with multiple bodies and multiple wave directions. Like the rest of BEMIO, it cannot currently handle generalized degrees of freedom; all bodies most have all six degrees of freedom. The case-study and verification in this paper is for a single body and single wave direction. For simplicity results from a heave-only simulation case are shown.

4.1 Pressure Coefficients

The complex diffraction ($\tilde{\Psi}_D$) and radiation ($\tilde{\Psi}_{R_j}$) cell-by-cell pressure coefficients are imported by parsing BEM output files. The diffraction coefficients are a function of wave frequency and wave direction, and the radiation coefficients are a function of frequency, but for this application a single wave direction and frequency are used. The complex Froude-Krylov pressure coefficients, $\tilde{\Psi}_{FK}$, are then calculated for each cell (i) as,

$$|\tilde{\Psi}_{FK_i}| = \rho g \frac{\cosh(k(z_i + h))}{\cosh(kh)} \tag{1}$$

$$\angle\tilde{\Psi}_{FK_i} = kx_i \tag{2}$$

$$\tilde{\Psi}_{FK_i} = |\tilde{\Psi}_{FK_i}|\cos(\angle\tilde{\Psi}_{FK_i}) + i|\tilde{\Psi}_{FK_i}|\sin(\angle\tilde{\Psi}_{FK_i}) \tag{3}$$

where ρ, g, k, and h are the water density, gravitational acceleration, wave number, and water depth, and z_i and x_i are the cell depth from the still water line and the cell location along the direction of wave propagation. The cell-by-cell excitation pressure coefficients are then given as the sum of the parsed diffraction pressures and the calculated Froude-Krylov pressures.

Although for the regular wave implementation it is possible to work with complex coefficients (e.g. there is no need to separate radiation into damping and added mass), the real-valued coefficient implementation is used here for generality. The four real-valued pressure coefficients needed for the time-domain implementation are obtained for each cell (i) and each degree of freedom (j) as

$$C_{rd_{i,j}} = \Re\{\tilde{\Psi}_{R_{i,j}}\} \tag{4}$$

$$C_{am_{i,j}} = \frac{-\Im\{\tilde{\Psi}_{R_{i,j}}\}}{\omega} \tag{5}$$

$$C_{rex_i} = \Re\{\tilde{\Psi}_{FK_i} + \tilde{\Psi}_{D_i}\} \tag{6}$$

$$C_{iex_i} = \Im\{\tilde{\Psi}_{FK_i} + \tilde{\Psi}_{D_i}\} \tag{7}$$

where C_{rd}, C_{am}, C_{rex}, and C_{iex} are the real-valued radiation damping, added mass, real excitation, and imaginary excitation pressure coefficients, and ω is the wave frequency.

To verify that all the pressure coefficients were parsed or calculated correctly, the pressures can be integrated and compared to the NEMOH whole-body coefficients. For a single wave direction the excitation coefficients are a 6×1 vector. For a single body the radiation damping and added mass coefficients are 6×6 matrices. The pressures are integrated to obtain whole-body force ($\overrightarrow{F}$) and moment ($\overrightarrow{M}$) by calculating the force and moment vectors at each cell, and summing over the entire surface as

$$\overrightarrow{F} = \sum_{i=1}^{N}(C_i A_i \hat{n}_i) = \sum_{i=1}^{N}\overrightarrow{F_{c_i}} \tag{8}$$

$$\overrightarrow{M} = \sum_{i=1}^{N}(\overrightarrow{F_{c_i}} \times \overrightarrow{cg_i}) \tag{9}$$

where C_i, A_i, $\hat{n}_i$, N, $\overrightarrow{F_{c_i}}$, and $\overrightarrow{cg_i}$ are the pressure coefficients, cell areas, cell normal vectors, number of cells, force vectors at cells, and center of gravity to cell centroid vectors.

Figure 2 shows a comparison of the coefficients for the heave-only case obtained from NEMOH and those calculated through pressure integration as described above.[1] Both radiation and excitation coefficients match well, indicating that the pressures were parsed, calculated, and integrated correctly.

4.2 Pressure Time-History

If the time history of the body motion under a regular wave, $x_j(t)$, is known, the time-histories of the distributed pressures at each cell can be found as follows:

$$P_{rd_{i,j}}(t) = C_{rd_{i,j}}\dot{x}_j(t) \tag{10}$$

$$P_{am_{i,j}}(t) = C_{am_{i,j}}\ddot{x}_j(t) \tag{11}$$

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[1] Note that some irregular frequency effects are visible in the BEM results (e.g. $\sim 6\,\mathrm{Hz}$), however, these do not affect the analysis performed here.

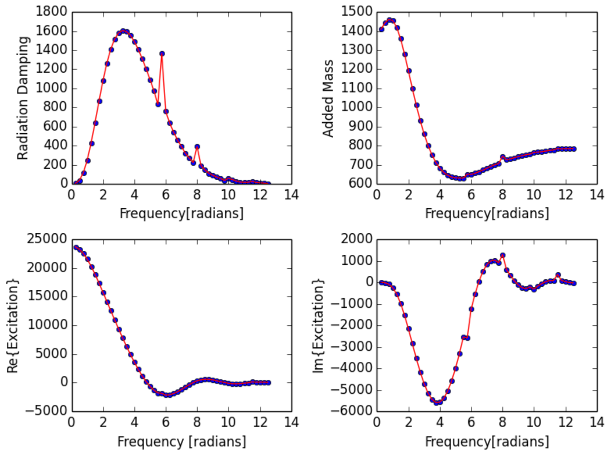

Figure 2: Comparison of heave-heave radiation and excitation coefficients from NEMOH (blue dots) and from pressure integration (red line).

$$P_{ex_i}(t) = A(C_{rex_i}\cos(\omega t) - C_{iex_i}\sin(\omega t)) \qquad (12)$$

$$P_{hs_i}(t) = \begin{cases} -x_{i_3}(t)\rho g & \text{if} \quad x_{i_3} < 0 \\ 0 & \text{if} \quad x_{i_3} \geq 0 \end{cases} \qquad (13)$$

$$P_{T_i}(t) = P_{ex_i}(t) + \sum_{j=1}^{6}(P_{rd_{i,j}}(t) + P_{am_{i,j}}(t)) + P_{hs_i}(t) \qquad (14)$$

Here, $P_{rd_{i,j}}$, $P_{am_{i,j}}$, P_{ex_i}, and P_{hs_i} are the radiation, added mass, excitation, and hydrostatic components of pressure at cell i, P_{T_i} is the total pressure at cell i, A is the wave amplitude, and $x_{i_3}(t)$ is the vertical position of cell i at time t. The hydrostatic pressure, as given by (13), is calculated by using the instantaneous position of the each cell and the mean water line. Distributed force time-histories for each cell can be obtained by multiplying the pressure time-histories times the cell area, and cell normal vector. Figure 3 shows the distributed excitation pressure over the WEC geometry for a single time-step.

In order to verify the implementation, a WEC-Sim [5] simulation of the device was performed with a regular wave of amplitude 0.05 m and period 1.57 s. The pressure time-histories were integrated at each time-step as in (8) and (9) to obtain force and moment time-histories for the whole body. The results were compared to the force time-histories from the WEC-Sim simulation. This was done for total pressure as well as the individual pressure components. The results for the different force components are shown in Figure 4, and for the total force in Figure 5. The hydrostatic force obtained from pressure integration is the total hydrostatic force, and $\rho g V$ had to be added to the WEC-Sim hydrostatic force for comparison, where V is the displaced volume at the equilibrium position.

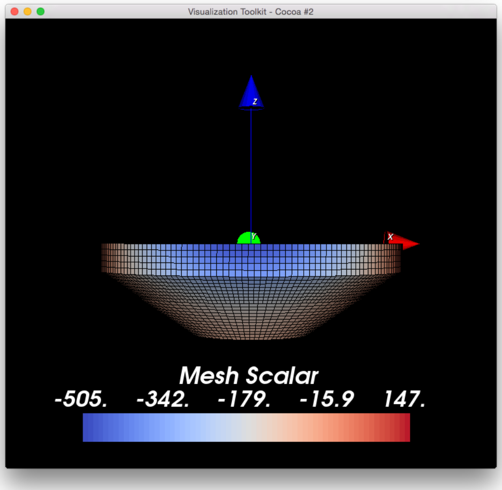

Figure 3: Excitation pressure distribution at end of simulation ($t = 15\,\text{s}$).

5. STRUCTURAL ANALYSIS

In order to showcase a possible application of the distributed pressure tool, a transient structural dynamic analysis has been conducted in the commercial software ANSYS. The dynamic pressure obtained as described in the previous section was applied to the submerged surface. A solid model is used in ANSYS and meshed with SOLID185 elements. The mass density is set to 674 kg/m^3 to match the total weight of the WEC; the Young's modulus and Poission's ratio are set to 70×10^9 Pa and 0.3, respectively. The simulation range is $[0, 15]$ s and the time step size is 0.05 s. The results of the structural analysis are shown in Figures 6-8. Figure 6 shows the contour plot of the x-displacement at the end of simulation ($t = 15\,\text{s}$) viewing from the bottom of the converter. Figure 7 shows a similar contour plot of the Von Mises stress. Figure 8 shows the transient z-direction displacement at the center of the bottom surface of the structure.

6. SUMMARY

In this paper, a tool for obtaining pressure distributions on WECs from mid-fidelity simulations is presented. The theory and implementation are presented and results from a verification case are shown. This tool provides the ability to obtain pressure distributions and perform structural analysis without having to run high-fidelity fluid dynamics codes. The only requirements are the motions obtained from a low/mid-fidelity code, such as WEC-Sim, and the results from the BEM code. As an example of a possible application, the pressures obtained with this tool were imported into the FEA code ANSYS to analyze the structural response of the WEC. The code is being expanded to handle irregular waves, and once completed will be made publicly available. The tool will also be expanded to work with the other two BEM codes BEMIO uses (WAMIT and AQWA).

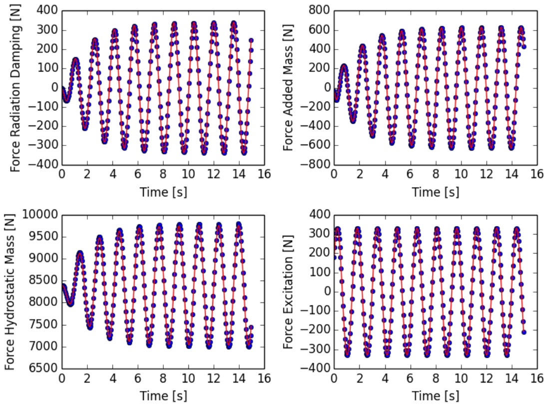

Figure 4: Comparison of the different force components time histories from WEC-Sim (blue dots) and from pressure integration (red line).

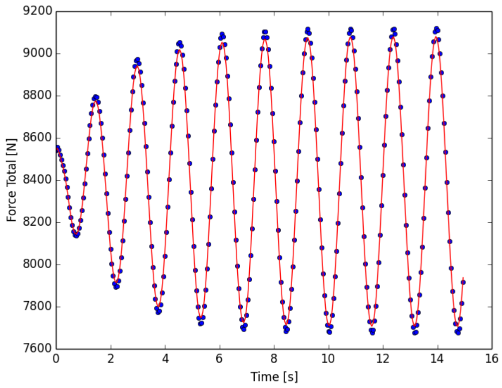

Figure 5: Comparison of total force time history from WEC-Sim (blue dots) and from pressure integration (red line).

7. ACKNOWLEDGMENT

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8. REFERENCES

[1] Cummins, WE, 1962. "The Impulse Response Function and Ship Motions". *Schiffstechnik,* *47*(9), pp. 101–109.

[2] Lawson, M., Yu, Y.-H., and Michelen, C., 2015. BEMIO Documentation, http://wec-sim.github.io/bemio/.

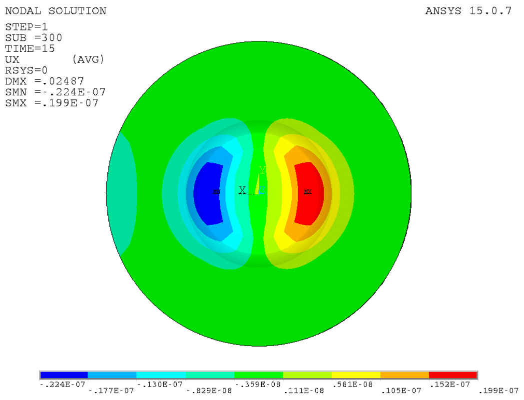

Figure 6: Results from demonstration FEA analysis: x-displacement at $t = 15\,\text{s}$.

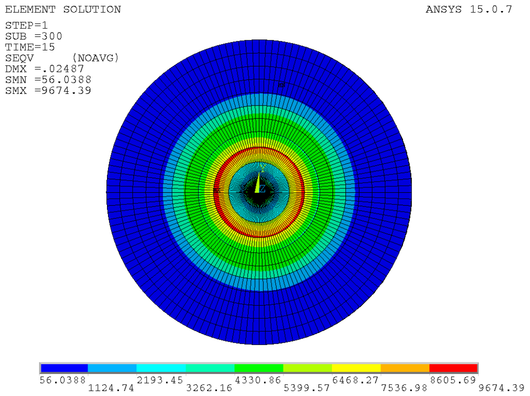

Figure 7: Results from demonstration FEA analysis: Von Mises stress at $t = 15\,\text{s}$.

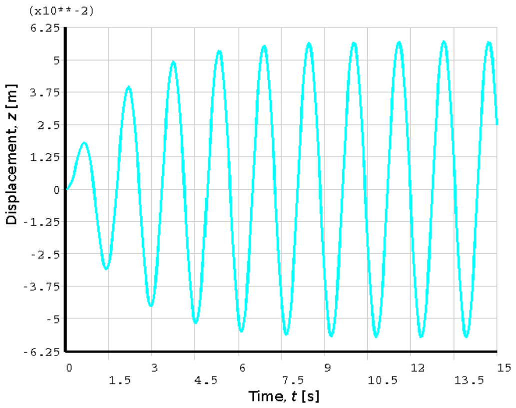

Figure 8: Results from demonstration FEA analysis: time-history of z-direction displacement at the center of the bottom surface.

[3] Babarit, A., and Delhommeau, G., 2015. “Theoretical and numerical aspects of the open source BEM solver NEMOH”. In 11th European Wave and Tidal Energy Conference (EWTEC2015), Nantes, France.

[4] Bull, D. L., Coe, R. G., Monda, M., Dullea, K., Bacelli, G., and Patterson, D., 2015. “Design of a physical point-absorbing wec model on which multiple control strategies will be tested at large scale in the mask basin”. In International Offshore and Polar Engineering Conference (ISOPE2015).

[5] Lawson, M., Yu, Y.-H., Kelley, R., and Michelen, C., 2014. “Development and demonstration of the WEC-Sim wave energy converter simulation tool”. In Proceedings of the 2$^{\text{nd}}$ Marine Energy Technology Symposium.