Effects of Inside-Ship Oscillator Placement on Wave Energy Harvesting

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HIGHLIGHTS

This study establishes the coupled mathematical model for dynamic interaction of a wave-energy-harvesting oscillator inside ship under regular waves. The impact of the oscillator's longitudinal placement on wave energy harvesting is assessed. The results demonstrate that installation near the stem can improve performance.

1 INTRODUCTION

Innovative concepts for integrating wave energy with ships have emerged, highlighting its potential as an auxiliary power source. Sharon et al. developed foldable point absorbers on ship decks [1], capable of generating up to 1 MW while docked. A team from the University of Tokyo designed a motion-controlled catamaran capturing energy from relative hull motion [2-4], while its structure is complex. Wu et al. proposed a back-bent tube wave energy ship [5], using oscillating water column principles for high efficiency and low costs, but requiring significant internal space. Li et al. introduced an arc-slideway device for modest energy output from rolling motion [6].

Recently, Liu et al. proposed an onboard mass-spring-damper oscillator to convert vertical motion into electricity [7]. Installed inside the ship, it operates without affecting hydrodynamics or maneuverability, generating power during voyages or while docked. However, the impact of oscillator positioning at the stem or stern on performance remains unexplored. This study uses the boundary element method (BEM) to derive a mathematical model for the coupled wave-ship-oscillator system and investigates how longitudinal positioning influences energy capture.

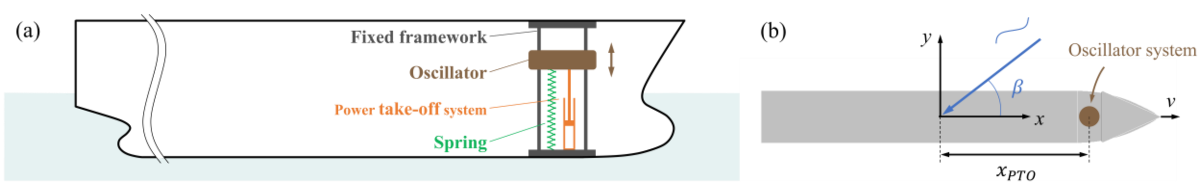

Figure 1: (a) An energy-harvesting oscillation system inside ship from front view; (b) Directions of wave propagation and ship heading from top view.

2 MATHEMATICAL MODEL

As shown in Figure 1a, a fixed frame between the ship's bottom plate and deck supports a vertically sliding oscillator, with springs providing restoring forces and a power take-off (PTO) system converting kinetic energy into electricity. The coordinate system is located at the ship's center of gravity, with x-axis pointing in the ship's heading direction. The installation position of the oscillator system is shown in Figure 1b, with a longitudinal distance of x_{PTO} from y-axis. v is the forward speed; β is the wave encounter angle.

2.1 Dynamic Equation of Ship

Since the oscillator's motion is primarily driven in the vertical direction, only the ship's heave and pitch degrees of freedom are considered, while the effects of other degrees of freedom are neglected. The time-domain dynamic equation of ship is given by

$$\begin{bmatrix} m+\mu_{33}(|\omega_e|) & \mu_{35}(|\omega_e|) \\ \mu_{53}(|\omega_e|) & I_{yy}+\mu_{55}(|\omega_e|) \end{bmatrix}\begin{Bmatrix} \ddot{u}_3(t) \\ \ddot{u}_5(t) \end{Bmatrix}+\begin{bmatrix} c_{33}(|\omega_e|) & c_{35}(|\omega_e|) \\ c_{53}(|\omega_e|) & c_{55}(|\omega_e|) \end{bmatrix}\begin{Bmatrix} \dot{u}_3(t) \\ \dot{u}_5(t) \end{Bmatrix} + \begin{bmatrix} k_{33} & k_{35} \\ k_{53} & k_{55} \end{bmatrix}\begin{Bmatrix} u_3(t) \\ u_5(t) \end{Bmatrix} = A\begin{Bmatrix} f_3(\omega,\beta)\cos[-\omega_e t+\phi_3(\omega,\beta)] \\ f_5(\omega,\beta)\cos[-\omega_e t+\phi_5(\omega,\beta)] \end{Bmatrix} + \boldsymbol{F}_{PTO}(t) \tag{1}$$

where m and I_{yy} represent the ship hull mass and the inertia torque about its gravity center in pitch, respectively, accounting the fixed framework, spring, and PTO system but exclude oscillator. $u_3(t)$ and $u_5(t)$ denote the ship displacement in heave and pitch, respectively; A is the wave amplitude; $f_i(\omega,\beta)$ is the amplitude of the wave-exciting force/moment coefficient, while $\phi_i(\omega,\beta)$ is the corresponding phase, where ω is the incident wave frequency; ω_e is the wave encounter frequency, given by $\omega_e=\omega+vk\cos\beta$, where k is the wave number, and at deep water, $k=\omega^2/g$, with g being gravity acceleration; $\mu_{ij}(|\omega_e|)$ and $c_{ij}(|\omega_e|)$ are the added mass and radiation damping coefficients at the wave encounter frequency, respectively; Stiffness coefficients $k_{33}=\rho g A_{WL}$; $k_{35}=k_{53}=\rho g\int(x-x_g)n_z ds$; $k_{55}=\rho g(z_b-z_g)\nabla-\rho g\int(x-x_g)^2 n_z ds$; ρ is the water density; A_{WL} is the waterline area; s is the wetted surface in calm water; n_z is the z-axis component in unit normal vector of the wetted surface elements pointing outwards; x is the initial x-coordinate of a wetted surface element centroid; x_g and z_g are the x- and z-coordinates of gravitational center; z_b is the z-coordinate of buoyancy center; ∇ is the displacement volume. $\boldsymbol{F}_{PTO}(t)$ is the total force acting on the ship from the oscillator system.

2.2 Dynamic Equation of Oscillator System

Simplifying the PTO system as a constant damper, the oscillator system can be recognized as a mass-spring-damper system. The time-domain dynamic equation of oscillator is given by

$$m_{PTO}[\ddot{u}_3(t)-\ddot{u}_5(t)x_{PTO}+\ddot{u}_{PTO}(t)]+C_{PTO}\dot{u}_{PTO}(t)+K_{PTO}u_{PTO}(t)=0 \tag{2}$$

where m_{PTO} is the oscillator mass; $u_{PTO}(t)$ is the oscillator displacement; C_{PTO} is the PTO damping; K_{PTO} is the spring stiffness. To ensure the ship's overall inertia remains unchanged, the following conditions are satisfied: $m+m_{PTO}=\rho\nabla$ and $I_{yy}+m_{PTO}{x_{PTO}}^2=\rho\nabla {k_{yy}}^2$, where k_{yy} is the radius of ship pitch gyration.

The total force acting on the ship from the oscillator system is given by

$$\boldsymbol{F}_{PTO}(t)=\{C_{PTO}\dot{u}_{PTO}(t)+K_{PTO}u_{PTO}(t),-[C_{PTO}\dot{u}_{PTO}(t)+K_{PTO}u_{PTO}(t)]x_{PTO}\}^T \tag{3}$$

2.3 Coupled Dynamic Equation

Substituting Eq. (3) into Eq. (1) and combining with Eq. (2), the frequency-domain coupled dynamic equation of ship and on-board oscillator is given by

$$\begin{bmatrix} q_{11} & q_{12} & q_{13} \\ q_{21} & q_{22} & q_{23} \\ q_{31} & q_{32} & q_{33} \end{bmatrix} \begin{Bmatrix} U_3 e^{i\theta_3} \\ U_5 e^{i\theta_5} \\ U_{PTO} e^{i\theta_{PTO}} \end{Bmatrix} = A \begin{Bmatrix} f_3(\omega,\beta) e^{i[-\phi_3(\omega,\beta)+\pi/2]} \\ f_5(\omega,\beta) e^{i[-\phi_5(\omega,\beta)+\pi/2]} \\ 0 \end{Bmatrix} \tag{4}$$

where $q_{11} = -\omega_e{}^2[m + \mu_{33}(|\omega_e|)] + i\omega_e c_{33}(|\omega_e|) + k_{33}$; $q_{12} = -\omega_e{}^2\mu_{35}(|\omega_e|) + i\omega_e c_{35}(|\omega_e|) + k_{35}$; $q_{13} = -i\omega_e C_{PTO} - K_{PTO}$; $q_{21} = -\omega_e{}^2\mu_{53}(|\omega_e|) + i\omega_e c_{53}(|\omega_e|) + k_{53}$; $q_{22} = -\omega_e{}^2\left[I_{yy} + \mu_{55}(|\omega_e|)\right] + i\omega_e c_{55}(|\omega_e|) + k_{55}$; $q_{23} = x_{PTO}(i\omega_e C_{PTO} + K_{PTO})$; $q_{31} = -\omega_e{}^2 m_{PTO}$; $q_{32} = \omega_e{}^2 x_{PTO} m_{PTO}$; $q_{33} = -\omega_e{}^2 m_{PTO} + i\omega_e C_{PTO} + K_{PTO}$; U_i is the amplitude of ship/oscillator, assuming a sinusoidal response, while θ_i denotes the corresponding phase.

Hydrodynamic coefficients $\mu_{ij}(|\omega_e|)$ and $c_{ij}(|\omega_e|)$, $f_i(\omega,\beta)$, and $\phi_i(\omega,\beta)$ are obtained from NEMOH, an open-source BEM tool. A Python code was developed to solve the equation.

2.4 Energy Harvesting Performance

To estimate the wave energy capture performance, the capture width (CW) is defined by

$$CW = \frac{P_c}{P_w} \tag{5}$$

where P_c is the capturing power, given by $P_c = C_{PTO} U_{PTO}{}^2 \omega_e{}^2/2$; P_w is the incident wave power per unit width for regular waves at deep water [8], given by $P_w = \rho g A^2 \omega/(4k)$.

3 VALIDATIONS

A 1:37.89 scale model of the KRISO Container Ship (KCS) without onboard oscillator was used for validation, tested in a wave basin at a towing speed of 2.017 m/s with regular waves having an incident wave period of 2.309 s and a wave amplitude of 0.0745 m. The full-scale KCS is a 230-meter-long containership with $\nabla = 52{,}030$ m^3 and $k_{yy} = 57.5$ m [9]. Figure 2 compares the ship's heave and pitch responses between the mathematical model and experimental data. The numerical model slightly overestimates the amplitudes, due to the neglect of fluid viscosity effects. However, these discrepancies are within acceptable limits, given the high computational efficiency.

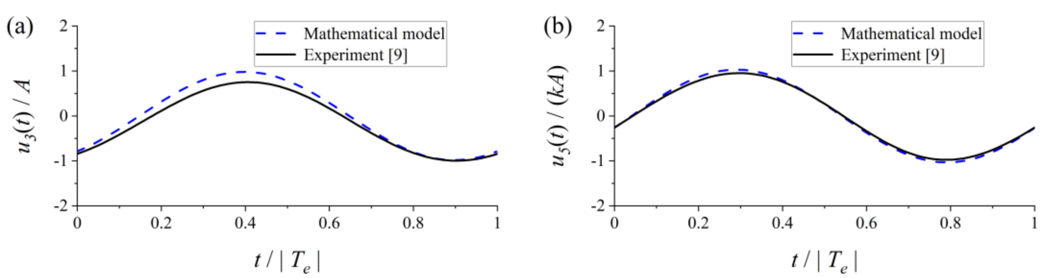

Figure 2: Comparison of the small-scale KCS response between the mathematical model and experimental data [9]: (a) Heave; (b) Pitch.

4 EFFECTS OF OSCILLATOR PLACEMENTS

For a full-scale voyaging KCS ($V = 24$ knots) under various wave conditions, an oscillator system with $m_{PTO} = 750$ t and $K_{PTO} = 400$ kN/m is designed, with C_{PTO} adjustable based on the wave climate to maximize energy capture performance. However, due to the limited stroke length of the oscillator, it must be sufficiently large to ensure the constraint $U_{PTO} \leq 3$ m. The maximum CWs are obtained by scanning PTO damping for each wave condition. Figure 3 compares the maximum CWs for different oscillator placements. When positioned near the stem, the oscillator shows significantly better energy capture performance compared to placements at the stern or midship. The higher CW values are observed across a wider incident wave period range.

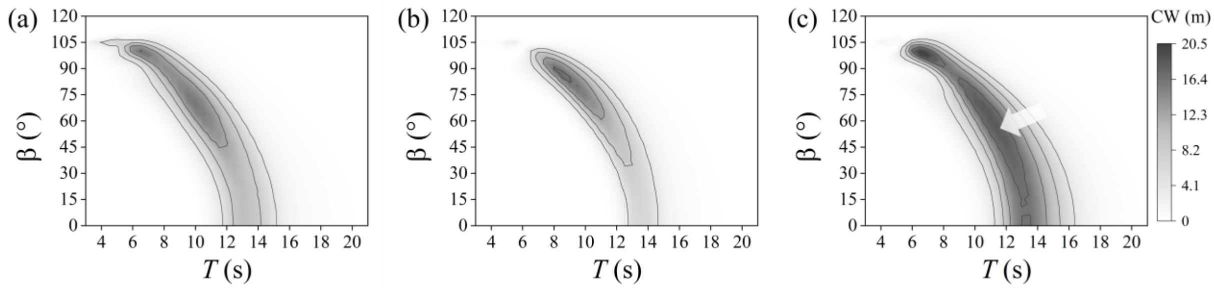

Figure 3: Comparison of maximum CWs (in m) of oscillator system inside full-scale KCS for difference oscillator placements: (a) Near stern $x_{PTO} = -80\ m$; (b) Amidship $x_{PTO} = 0$; (c) Near stem $x_{PTO} = 80\ m$.

5 CONCLUSIONS

Based on the BEM, this study develops a coupled mathematical model of a wave-energy-harvesting oscillator inside ship under regular waves. A fully open-source solution, utilizing NEMOH for calculating hydrodynamic coefficient and Python for solving the equations, was employed. The study focuses on evaluating the impact of the oscillator's longitudinal placement on wave energy harvesting. Numerical results show that positioning the oscillator near stem improves performance across a broader wave period range.

REFERENCES

[1] Sharon, A., Briggs, J., Wirz, H., & Fraunhofer, C. 2011. *Mobile Wave Energy Harvesting System*. CleanTech2011 Conf, 1–4.

[2] Han, J., Maeda, T., Kitazawa, D., & Kinoshita, T. 2015. *Analysis of a Motion-Controlled Ship for Wave Energy Harvesting-Based on an Application of MPPT*. Conference Proceedings The Japan Society of Naval Architects and Ocean Engineers 20, 333–336.

[3] Kanno, S., Han, J., Maeda, T., Yoshida, T., & Kitazawa, D. 2017. *Numerical Simulation of Motion-Controlled Fishery Boat With Harvesting Wave Energy*. Volume 6: Ocean Space Utilization, V006T05A007. https://doi.org/10.1115/OMAE2017-61824

[4] Han, J., Kitazawa, D., Kinoshita, T., Maeda, T., & Itakura, H. 2019. *Experimental investigation on a cabin-suspended catamaran in terms of motion reduction and wave energy harvesting by means of a semi-active motion control system*. Applied Ocean Research, 83, 88–102. https://doi.org/10.1016/j.apor.2018.12.003

[5] Wu, B., Chen, T., Jiang, J., Li, G., Zhang, Y., & Ye, Y. 2018. *Economic assessment of wave power boat based on the performance of "Mighty Whale" and BBDB*. Renewable and Sustainable Energy Reviews, 81, 946–953. https://doi.org/10.1016/j.rser.2017.08.051

[6] Li, B., Zhang, R., Zhang, B., Cui, Y., & Yang, Q. 2020. *A New Energy Recovery Device by Utilizing the Merchant Ship Rolling*. IEEE Access, 8, 162049–162065. https://doi.org/10.1109/ACCESS.2020.3021180

[7] Liu, Y., Chen, W., Zhang, X., Dong, G., & Jiang, J. 2023. *Wave energy conversion using heaving oscillator inside ship: Conceptual design, mathematical model and parametric study*. Renewable Energy, 219, 119526. https://doi.org/10.1016/j.renene.2023.119526

[8] Newman, J. N. 2018. *Marine Hydrodynamics*. The MIT press, Cambridge, MA, USA.

[9] T2015 – KCS. https://www.t2015.nmri.go.jp/kcs.html