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# On wave energy focusing and conversion in open water

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ABSTRACT

This paper investigates wave energy conversion in open water where the goal is to utilize the wave-field focusing effect of a stationary disc submerged a short depth beneath the water surface. Dynamic interaction of the disc with additional coupled, submerged inertias is used to minimize its oscillation. The method used to enable and extend this favorable dynamic coupling is discussed here. An oscillating water column in a submerged duct attached under a small circular opening in the disc and driven by the wave-field over the disc is used for wave energy conversion. Non-real-time reactive control of the water column response to enhance energy absorption is examined. Added mass, radiation damping, and exciting force values for the submerged disc are computed, and the focusing effect of a submerged stationary disc is confirmed with numerical calculations of surface elevation over the disc. Calculations of hydrodynamic performance suggest that energy absorption from the oscillating water column is significantly greater under control holding the disc stationary, and can be improved further by applying reactive loads tuned to the optimal susceptance and conductance associated with the oscillating water column. Although the control forces involved in holding the disc stationary may be large at lower wave numbers, the maximum deflection amplitudes of the compensation system are found to be within reasonable limits.

## 1. Introduction

Wave energy conversion technology has undergone rapid development in recent years [1]. While many wave energy converter ('device') concepts have matured to the point of ocean testing, new ideas stressing particular goals continue to be proposed. Although wave energy conversion in many circumstances today is not as cost-effective as wind or solar energy conversion, considerable amount of research is being directed at improvements that would reduce the total life cycle operating cost of a wave energy converter. To minimize initial costs, it is important to reduce the structural costs (including any mooring costs) of the device. This may be accomplished by minimizing the size and weight of a device for the required amount of generated power. Broadly speaking, device size is often driven by the need to optimize energy transfer between incoming waves and the device. However, device weight is strongly influenced by extreme waves from which no energy is typically absorbed but which the device must survive in its lifetime. Due to their ability to respond compliantly to very large waves, floating devices (together with their mooring systems) can be structurally more efficient for a given size.

Active control of the device hydrodynamic response enables greater freedom with device size by optimizing wave-device energy transfer with the help of external control forces. This makes small structurally efficient axi-symmetric point absorber floating devices [2] with hydrodynamic control particularly attractive. Such devices have sharp resonance peaks (and hence narrow-band efficient absorption) around shorter wave periods, and control enhances their overall energy absorption by extending efficient absorption into the long period range, where the incident wave energy is greater. Active control thus can potentially enable a small device to operate with high efficiency in different wave spectra, effectively increasing the overall annual energy production even as wave spectra change with seasons.[1] This was demonstrated in simulations some time ago [5], and more recently, in sea trials on the 'Wave Star' device in Denmark [6].

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[1] Control applications for absorption efficiency improvement are reviewed in Refs. [3], while brief summary of the more recent control applications for performance improvement is provided in Refs. [1,4].

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## Nomenclature

| | |
|---|---|
| $\alpha_s$, $\alpha_q$, $\alpha_\psi$ | Chosen constants in the interval [0, 1] |
| $\eta$ | energy capture efficiency; capture width ratio |
| $\eta_{\max}$ | the theoretical maximum for the energy capture width ratio |
| $\gamma$ | Euler's constant |
| $\lambda$ | wave length |
| $\mu(\omega)$ | frequency dependent radiation damping for disc in heave |
| $\mu_\varphi(\omega)$ | frequency-dependent radiation damping of disc in pitch |
| $\nu(\omega)$ | frequency-dependent radiation damping for disc + tube in surge |
| $\nu_\varphi(\omega)$ | frequency-dependent radiation damping of tube in pitch |
| $\omega$ | angular frequency of incoming regular wave |
| $\omega_h$ | uncoupled natural frequency for heave compensation mass |
| $\omega_s$ | uncoupled natural frequency for surge compensation mass |
| $\omega_\psi$ | uncoupled natural frequency for pitch compensation inertia |
| $\phi_d$ | total velocity potential due to submerged stationary disc |
| $\phi_I$, $\phi_D$, $\phi_R$ | spatial parts of the incident, diffraction, and radiation potentials |
| $\phi_r$ | velocity potential due to radiation; here due to tube surge |
| $\psi$ | angular oscillation of the secondary inertia for pitch compensation |
| $\overline{q}_w(i\omega)$ | diffraction flow rate due to the disc structure |
| $\varepsilon$ | surface elevation magnification factor over tube due to focusing |
| $\varphi$ | pitch oscillation of structure comprised of disc and tube |
| $A$ | incident wave amplitude |
| $a(\infty)$ | infinite-frequency added mass for disc + tube in surge |
| $a(\omega)$ | frequency-dependent added mass for disc + tube in surge |
| $a_\varphi(\infty)$ | infinite-frequency added inertia of tube in pitch |
| $a_\varphi(\omega)$ | frequency-dependent added inertia of tube in pitch |
| $b(\infty)$ | infinite frequency added mass of secondary inertia for surge compensation |
| $c(\infty)$ | infinite frequency added mass of secondary inertia for heave compensation |
| $C_g$ | group velocity |
| $d$ | depth of disc submergence |
| $F_r$ | radiation wave force on disc in heave |
| $f_r$ | radiation wave force on tube in surge |
| $f_s$ | exciting wave force on tube in surge |
| $F_w$ | exciting wave force on disc in heave |
| $ff_h$ | control force applied on secondary inertia for heave compensation |
| $ff_s$ | control force applied on secondary inertia for surge compensation |
| $H$ | coupled admittance relating disc heave and air-flow flux due to it (radiation coupling term) |
| $h$ | water depth |
| $H_m$ | Hankel function of first kind and order m |
| $H_r(\omega)$, $H_i(\omega)$ | resistive and reactive components of radiation coupling term between disc heave and air-flow flux |
| $h_y(t)$ | impulse response function for radiation conduction for water column |
| $i(\infty)$ | infinite frequency added inertia of secondary inertia for pitch compensation |
| $I_G$ | moment of inertia in air of structure comprised disc and tube |
| $i_g$ | moment of inertia in air of secondary inertia for pitch compensation |
| $k$ | wave number; $2\pi/\lambda$ |
| $k_h$ | stiffness of spring coupling structure with secondary inertial in heave |
| $k_s$ | stiffness of spring coupling structure with secondary inertia in surge |
| $L$ | water column load applied by the power take-off in the air chamber |
| $L_d(\omega)$, $L_s(\omega)$ | resistive and reactive components of load applied on water column |
| $m(\infty)$ | infinite-frequency added mass for disc in heave |
| $m(\omega)$ | frequency dependent added mass for disc in heave |
| $m_q$ | rest mass of secondary inertia for heave compensation |
| $M_r$ | radiation moment for disc pitch |
| $m_r$ | radiation moment for tube pitch |
| $m_s$ | rest mass of structure comprised of disc and tube |
| $m_u$ | rest mass of secondary inertia for surge compensation |
| $M_w$ | exciting moment in pitch for disc |
| $M_\varphi$ | exciting moment in pitch for tube |
| $m_\varphi(\infty)$ | infinite-frequency added inertia of disc in pitch |
| $m_\varphi(\omega)$ | frequency-dependent added inertia of disc in pitch |
| $m_{ij}$, $\mu_{ij}$ | added mass and radiation damping tensors used in the numerical hydrodynamic calculations |
| $mm_\psi$ | control moment applied on secondary inertia for pitch compensation |
| $p$ | pressure in the air chamber where power is absorbed from the water column |
| $P_w$ | incident wave power per unit crest length |
| $P_{\text{abs}}(\omega)$ | power absorbed by the water column/device at frequency $\omega$ |
| $P_{\text{inc}}(\omega)$ | wave power incident over disc at frequency $\omega$ |
| $Q_D(i\omega)$ | water flow flux due to heave motion of disc |
| $q_h$ | oscillation of secondary inertia for heave compensation |
| $Q_R(i\omega)$ | total radiation flow flux due to heave |
| $q_s$ | oscillation of secondary inertia for surge compensation |
| $Q_t(i\omega)$ | water flow flux due to heave motion of tube |
| $Q_w$ | diffraction flow flux; i.e. flow flux into air chamber with device held fixed in waves |
| $Q_w$ | overall diffraction flow rate due to disc and tube |
| $q_w(i\omega)$ | diffraction flow rate due to the tube |
| $R$ | disc radius |
| $S_D$ | plan area of the submerged disc; i.e. with a vertical unit normal vector |
| $s_h$ | heave oscillation of structure comprised of disc and tube |
| $s_s$ | surge oscillation of structure comprised of disc and tube |
| $S_T$ | plan area of tube opening |
| $Y$ | radiation admittance of the water column relating chamber pressure and water column flow flux due to it |