An energy focusing submerged wave energy device with active control

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Abstract

Recent years have seen a considerable resurgence of interest in ocean wave energy conversion systems world wide. Active control of device dynamics can enable smaller, more cost-effective, devices to absorb greater power from the available wave resource. In this poster, we discuss wave energy conversion based on an actively controlled system of dynamically coupled submerged bodies. It is known that submerged, near-surface, stationary circular discs can cause considerable wave-field focusing in their immediate neighborhood. In the three-body axisymmetric device considered here, the vertical oscillations of the bottom disc are controlled to hold the top disc nearly stationary over a wide range of incident wave frequencies. This enables the device to focus the incident wave field over a range of frequencies. We examine here active control using feedback of the absolute position and acceleration of the bottom disc. The oscillations of the middle disc, in response to the focused wave field, are utilized for energy conversion by hydraulic rams or linear generators supported from the top disc. While time domain control of the middle disc for optimal conversion will require wave elevation/oscillation prediction, frequency-domain control and tuning may be accomplished without prediction. Approximate analysis results for capture efficiency under frequency-domain control are discussed.

Introduction

Wave Energy

- Solar → wind → waves; densest resource of three, less variable than wind.
- Numerous ideas spanning centuries; most: wave motion → mechanical/usable motion (e.g. buoy heave, duck pitch, air flow).
- Recent at-sea trials: heaving buoy with linear generator, Pelamis 'spine' with hydraulics, oscillating water columns with air turbines.
- Considerable fundamental research over last 4 decades on primary energy conversion.

Conversion Efficiency

- High efficiency conversion critical for competitive cost/kWh.
  - high performance through near-resonance operation in wave spectra expected all year round.
  - minimize initial costs by minimizing device size (and structural costs) for specified power rating.
- active control: in addition to appropriate geometries for optimum hydrodynamic performance, control power absorbing load so oscillator velocity in phase with wave-applied excitation force.

Active Control

- Fraught with fundamental problems[1], [2].
- Body oscillated by incoming waves forces water with own motion to make waves.
- Radiation impulse response function is causal and with 'memory effect'.
- Complex conjugate impedance match only straightforward in harmonic waves of known frequency.
- Wave-by-wave phase control or time-domain optimal control requires oscillation/incoming wave prediction few seconds into the future, which is difficult in irregular/random waves.
- Suboptimal control without prediction in the time domain, or frequency-domain tuning practical.

Present Goal and Method

- Investigate whether frequency-domain tuning of the device + engineered focusing of incident wave energy around it → hydrodynamic and economic performance comparable to time-domain optimal control without focusing.

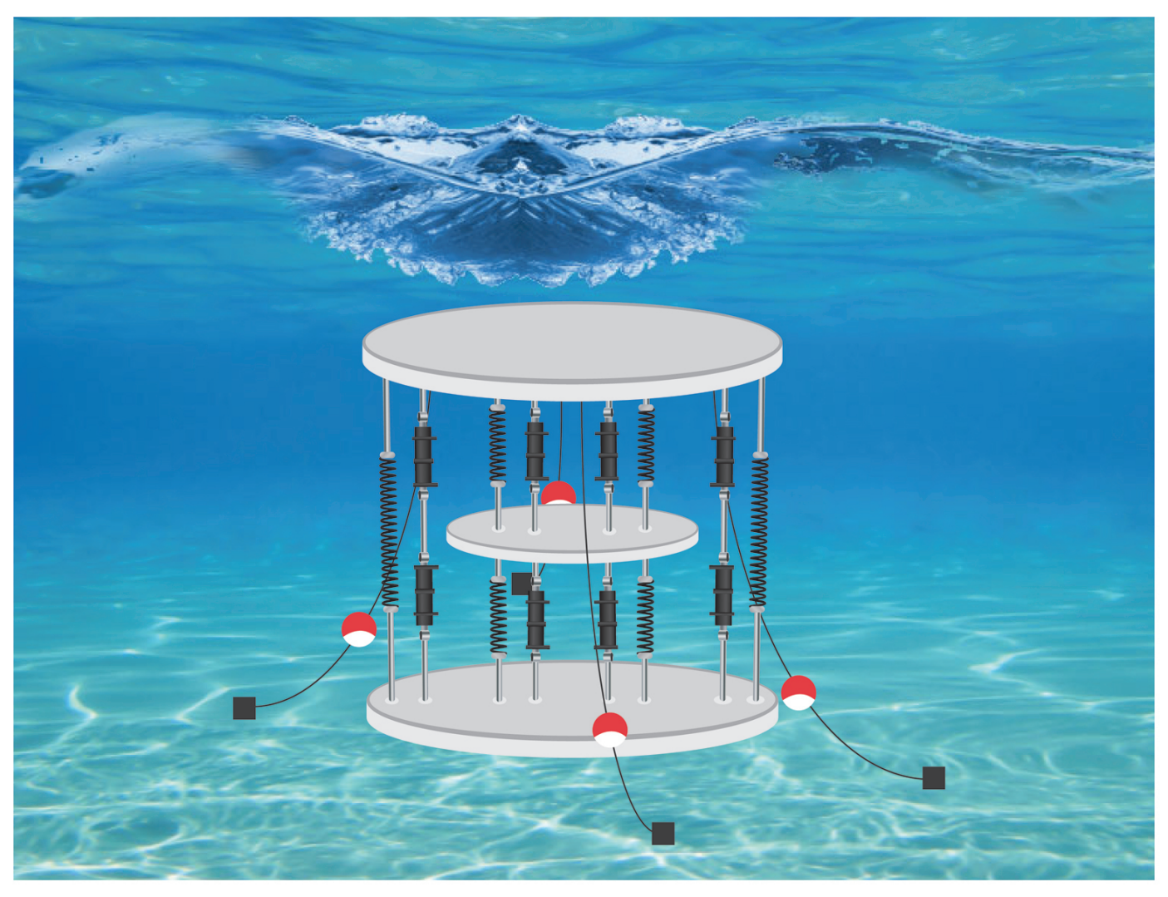

Figure 1: A three-body system to focus waves and enable conversion of focused energy. Control extends this operation to a wider frequency range.

- Dynamically coupled submerged discs, predominantly heaving.
- A fixed top disc focuses wave field just behind center[3]; at some frequencies, 2–3 fold amplification.
- Natural dynamic coupling between top and bottom discs holds top disc fixed in heave at one frequency.
- Use control to extend this action to a wider frequency range.
- Bottom disc deep enough to cause negligible wave radiation ⇒ no prediction required for time-domain control of its oscillation.
- Absolute position and acceleration of bottom disc sensed relative to the sea bottom.
- Oscillations of middle disc relative to top disc for energy absorption, with frequency-domain tuning of middle disc for sub-optimal control.
- Air springs as coupling springs and hydraulic actuators for power absorption.

Mathematical Model

Approximate analysis to compare performance with and without active control.

$$\begin{aligned}(m_s+m_\infty)\ddot{s} &= F_w+F_R-k_q(s-q)\\ &\quad -k_u(s-u)-f_a-f_m\\ (m_u+b_\infty)\ddot{u} &= f_w+f_r+k_u(s-u)+f_a\\ (m_q+a_\infty)\ddot{q} &= f_d+f_q+k_q(s-q)+f_m \end{aligned} \tag{1}$$

The power absorbing actuator force can be given the following general form,

$$f_a(t)=L_s(s-u)+L_d(\dot{s}-\dot{u}) \tag{2}$$

For harmonic excitation (regular waves)

$$F_R(i\omega)=[i\omega\mu(\omega)-\omega^2 m(\omega)]S(i\omega) \tag{3}$$

for the top disc, and for the middle disc, as

$$f_R(i\omega)=[i\omega\nu(\omega)-\omega^2 b(\omega)]U(i\omega) \tag{4}$$

With $f_m=0$ (i.e. no control force applied on the bottom disc).

$$\mathbf{Z}(i\omega)\mathbf{S}(i\omega)=\mathbf{F}(i\omega) \tag{5}$$

Solving, it can be seen that at an excitation frequency $\omega=\sqrt{k_q/(m_q+a_\infty)}$,

$$\begin{aligned} S(i\omega) &= 0,\ \text{and}\\ U(i\omega) &= \frac{-Z_{31}^2(i\omega)F_u(i\omega)}{D(i\omega)} \end{aligned} \tag{6}$$

$$Q(i\omega)=\frac{Z_{31}(i\omega)\left[Z_{12}(i\omega)F_u(i\omega)-Z_{22}(i\omega)F_W(i\omega)\right]}{D(i\omega)} \tag{7}$$

⇒, the top disc is fixed in heave at the wave frequency ω above. With $f_m=\Re[F_M e^{i\omega t}]$ and

$$F_M(i\omega)=-\alpha\left(-\omega^2(m_q+a_\infty)+k_q\right)Q(i\omega) \tag{8}$$

As the fraction $\alpha\to 1$, $S(i\omega)\to 0$, and $U(i\omega)\to\frac{-Z_{31}^2(i\omega)F_u(i\omega)}{D(i\omega)}$, with $Q(i\omega)$ still given by equation (7). Using measured absolute deflection and acceleration of the bottom disc m_q (ultrasonic transducer and accelerometers, respectively),

$$\begin{aligned} f_m(t) &= \int_{-\infty}^{t} h_a(\tau)\ddot{q}(t-\tau)d\tau\\ &\quad +\int_{-\infty}^{t} h_q(\tau)q(t-\tau)d\tau \end{aligned} \tag{9}$$

And because m_q is far enough below the free surface,

$$\begin{aligned} h_a(\tau) &= H_a\delta(\tau-0),\ \text{and}\\ h_q(\tau) &= H_q\delta(\tau-0)\\ \Rightarrow f_m(t) &= H_a\ddot{q}(t)+H_q q(t) \end{aligned} \tag{10}$$

where $H_a=m_q+a_\infty$, and $H_q=k_q$. Power absorbed by the device and the power incident on it are found using,

$$P_{abs}(\omega)=\frac{1}{2}\omega^2 L_d\left|S(i\omega)-U(i\omega)\right|^2 \tag{11}$$

Finding incident power P_{inc} from known relationships, we can define the energy capture efficiency as, $\eta=P_{abs}/P_{inc}$ with the theoretical maximum given by $1/k$.

Results and Discussion

- Published diffraction force results for a submerged disc [4].
- Same results used to evaluate frequency dependent radiation damping and added mass based on known results linking diffraction and radiation quantities and causality of radiation impulse response.

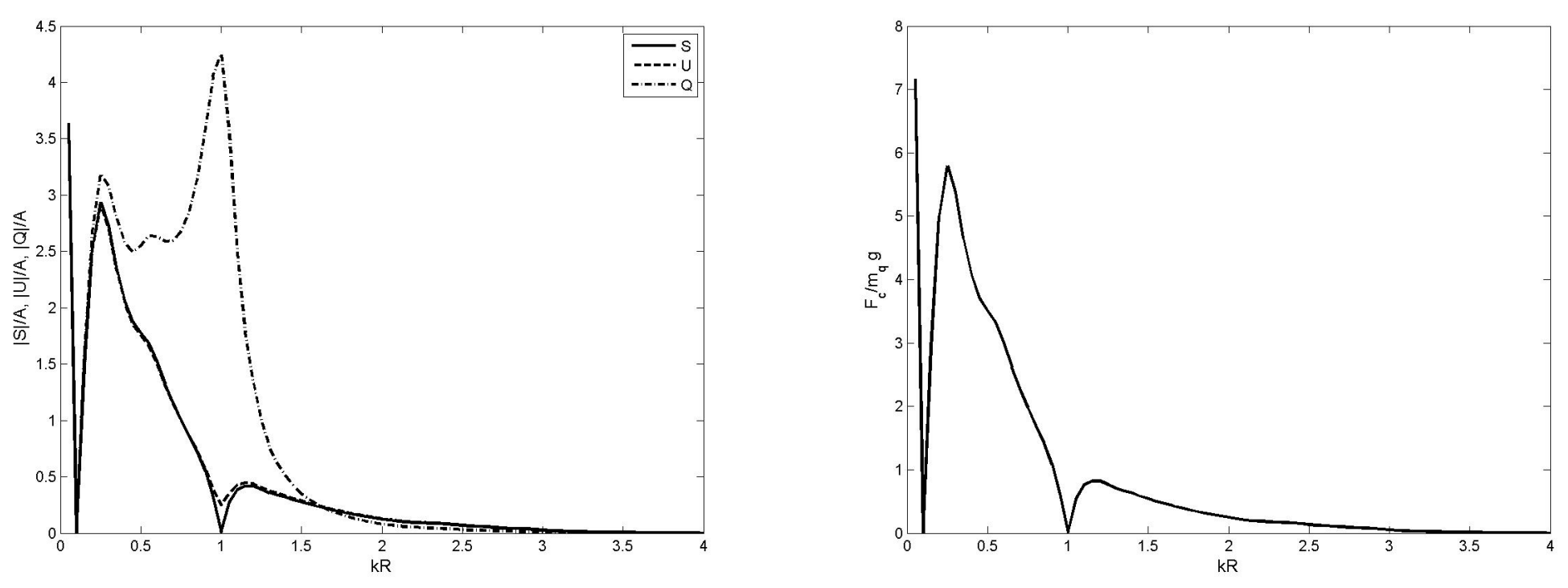

Figure 2: (Left) Deflection amplitudes of three discs without control force f_m; (Right) Magnitude of control force f_m needed to hold top disc fixed in heave.

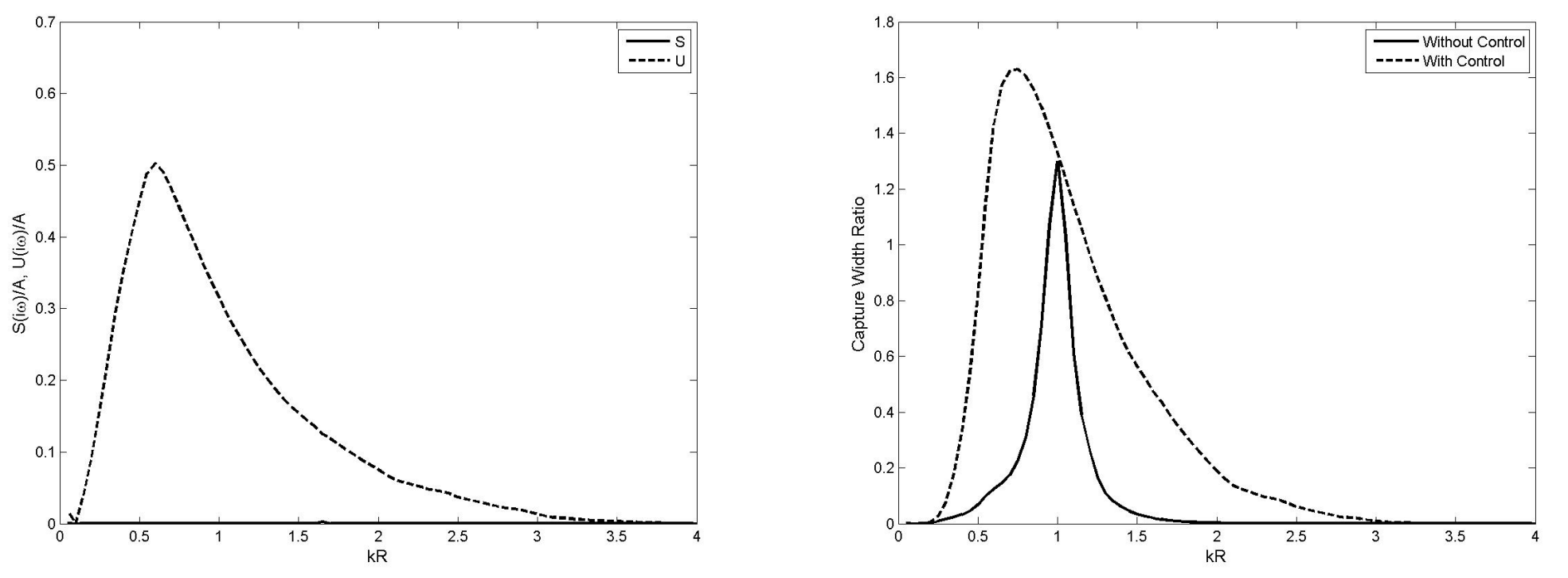

Figure 3: (Left) Deflection amplitudes of the top and middle discs with control force f_m; (Right) Energy capture factor with control of m_q, compared with that without.

- Top and bottom discs 6m, middle disc 4m in radius; water depth 6m (to be compatible with the Zhang and WIlliams diffraction force results); though no inherent constraints on these parameters.
- Bottom disc m_q (and spring k_q) tuned to $kR=1$ (wave period of 5.91 s); largest control force f_m about 3.5 times weight of bottom disc.
- Without control, 60% drop in capture factor over just $kR\pm 0.12$ (narrow bandwidth).
- With control of m_q, 60% drop over $kR\pm 082$ (considerably greater bandwidth).
- Improvement in capture factor with negative spring loads on middle disc.

Conclusions

- Two goals: Independent of water depth, (i) achieve local focusing of wave energy with a submerged disc, and (ii) extend frequency range of focusing with a dynamically coupled bottom disc.
- Reactively loaded middle disc for energy absorption with top disc as reference.
- More accurate calculations, experimental implementations, and variations on this concept currently being pursued.
- Reactive load control requires short-term energy storage.
- Longer-term storage and control required for connection to grid that meets prescribed dispatchability requirements.

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[1] J. Falnes, *Int. J. Offshore and Polar Engineering*, 12(2):147–155, 2002

[2] U.A. Korde, *Ocean Engineering*, 29(11): 1343-1355, 2001

[3] X. Yu and A Chwang, *J. Engineering Mechanics*, 119(9): 1804–1817, 1993

[4] S. Zhang and A.N. Williams, *J. Waterway, Port, Coastal, and Ocean Engineering*, 122(1): 38–45, 1996

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