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Pseudo-spectral control of a novel oscillating surge wave energy converter in regular waves for power optimization including load reduction

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ABSTRACT

The aim of this paper is to describe a procedure to maximize the power-to-load ratio of a novel wave energy converter (WEC) that combines an oscillating surge wave energy converter with variable structural components. The control of the power-take-off torque will be on a wave-to-wave timescale, whereas the structure will be controlled statically such that the geometry remains the same throughout the wave period. Linear hydrodynamic theory is used to calculate the upper and lower bounds for the time-averaged absorbed power and surge foundation loads while assuming that the WEC motion remains sinusoidal. Previous work using pseudo-spectral techniques to solve the optimal control problem focused solely on maximizing absorbed energy. This work extends the optimal control problem to include a measure of the surge foundation force in the optimization. The objective function includes two competing terms that force the optimizer to maximize power capture while minimizing structural loads. A penalty weight was included with the surge foundation force that allows control of the optimizer performance based on whether emphasis should be placed on power absorption or load shedding. Results from pseudo-spectral optimal control indicate that a unit reduction in time-averaged power can be accompanied by a greater reduction in surge-foundation force.

1. Introduction

The success of future wave energy converter (WEC) technologies will require the development of advanced control methods and/or structures that adapt device performance to maximize energy generation in operational conditions while shedding hydrodynamic loads in extreme sea states to reduce the structural mass and overall cost (Musial et al., 2013). In an attempt to address some of these issues, researchers at the National Renewable Energy Laboratory have been developing a novel WEC concept that combines an oscillating surge wave energy converter (OSWEC) with variable geometry (Tom et al., 2016a, 2016b). The design of active control surfaces is expected to assist in tuning the hydrodynamic properties of the device to maximize power absorption in moderate wave climates while shedding loads in larger seas to increase the operational range. The concept of controllable airfoils applied to wave energy conversion has recently been pursued in Atargis Energy Corporation's cycloidal device (Siegel et al., 2011). The idea for large-scale geometric changes has been considered in the design of Weptos (Pecher et al., 2012), though the focus has been on its survival mode. The WEC concept used in this paper is more similar to a pitching device with a rotatable flap (Kurniawan and Moan, 2012); however, increasing the number of adjustable surfaces allows for greater refinement in the hydrodynamic properties. The development of nearshore OSWECs in recent years has been led by Aquamarine Power's Oyster (Whittaker and Folley, 2012), AW-Energy Oy's Waveroller (Lucas et al., 2012), and Resolute Marine Energy's Surge WEC (Ramudu, 2011). In addition, Langlee Wave Power (Pecher et al., 2010) and PolyGen Ltd are currently developing floating, multiflap OSWECs for deepwater deployment. However, these designs consist of a fixed geometrical body which generally do not operate as a resonant device (Gomes et al., 2015) and instead rely on control of the power-take-off (PTO) system to further optimize power capture.

The control of ocean energy harvesting devices has garnered significant attention in the marine engineering community and is considered necessary for an open-ocean deployment to be successful and economical. Samples of the types of control methodologies that have previously been investigated are complex conjugate (Falnes, 2002), latching (Babarit and Clément, 2006), declutching (Babarit et al., 2009), and inertial tuning (Kurniawan and Moan, 2012 and Flocard and Finnigan, 2012). Applying state-constrained optimization (Eidsmoen, 1996; Hals et al., 2011) to WEC control has gained significant traction in recent times as it provides the ability to include nonlinear constraints. This optimization has been pursued using

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Nomenclature

Symbol	Description
φ	Flap pitch angle
ρ_m	Structural mass density
h	Water depth
H	OSWEC height
t	OSWEC thickness
w	OSWEC width
w_f	Flap width
$\forall$	OSWEC displaced volume
t_f	Flap minor axis
H_f	Flap major axis
w_s	Side support width
I_{55}	Pitch mass moment of inertia
$\ddot{\zeta}_5$	Pitch angular acceleration
t	Time
τ_{e5}	Pitch wave-exciting toque
τ_{r55}	Wave radiation torque because of pitch motion
τ_h	Hydrostatic restoring torque
τ_m	Mechanical torque applied by the power-take-off device
ρ	Mass density of the working fluid
$\forall$	WEC displaced volume in calm water
r_b	Radial distance from the origin to the center of buoyancy
m	Mass of the wave energy converter
r_g	Radial distance from the origin to the center of gravity
g	Gravitational acceleration
ζ_5	Time-varying pitch angular displacement
C_{55}	Pitch hydrostatic restoring coefficient
μ_{55}	Pitch added moment of inertia
σ	Wave Angular Frequency
K_{r55}	Pitch radiation impulse response function
$\dot{\zeta}_5$	Time-varying pitch angular velocity
λ_{55}	Pitch wave radiation damping
K_{e5}	Pitch wave-excitation torque kernel
η	Time-varying incident wave elevation
X_1	Frequency-dependent complex surge wave-exciting force coefficient
ϕ_1	Frequency-dependent phase of the surge wave-exciting force coefficient
X_3	Frequency-dependent complex heave wave-exciting force coefficient
ϕ_3	Frequency-dependent phase of the heave wave-exciting force coefficient
X_5	Frequency-dependent complex pitch wave-exciting torque coefficient
ϕ_5	Frequency-dependent phase of the pitch wave-exciting torque coefficient
$\Re$	Real component
$\Im$	Imaginary component
ϕ_I	Incident wave potential
A	Wave amplitude
k	Wave number
λ_w	Wave length
ξ_5	Complex amplitude of the pitch angular displacement
C_g	Power-take-off linear spring coefficient
B_g	Power-take-off linear damping coefficient
P_T	Time-averaged absorbed power
T	Wave period
P_R	Time-averaged reactive power
P	Time-varying instantaneous power
P_w	Wave time-averaged power per-unit width
V_g	Wave group velocity
C_w	Nondimensional capture width: traditional capture width divided by OSWEC width
C_R	Nondimensional capture width for reactive power
$H(x)$	Heaviside step function
δ	Ratio between the constrained-to-optimal pitch angular velocity
$PA_\pm$	Positive and negative peak-to-average power ratio
X_{r1}	Complex surge reaction force per wave amplitude
X_{r3}	Complex heave reaction force per wave amplitude
μ_{15}	Frequency-dependent surge-pitch radiation added mass
λ_{15}	Frequency-dependent surge-pitch radiation wave damping
f_m	Static heave reaction force
f_{r1}	Time-varying surge reaction force
K_{e1}	Surge wave-excitation force kernel
K_{r15}	Surge-pitch radiation impulse response function
a_m	Complex amplitude of the PTO torque to eliminate the surge foundation force
E	Absorbed energy
N	Number of terms in the Fourier series
ς^c, ς^s	Pitch angular displacement cosine and sine Fourier coefficients
$\hat{\varsigma}$	Vector of pitch angular displacement Fourier coefficients
ψ^c, ψ^s	Pitch angular velocity cosine and sine Fourier coefficients
$\hat{\psi}$	Vector of pitch angular velocity Fourier coefficients
τ^c, τ^s	Power-take-off torque cosine and sine Fourier coefficients
$\hat{\tau}$	Vector of power-take-off torque Fourier coefficients
σ_0	Fundamental angular frequency
δ_{ij}	Kronecker delta
θ	Cosine and sine time Fourier modes
$\Phi(t)$	Vector of time Fourier terms that form the orthogonal basis
Γ	Time-derivative matrix
G_{55}	Pitch wave-radiation convolution integral matrix
$\hat{e}_5$	Pitch wave-exciting torque Fourier coefficients
M_{55}	Pitch equation of motion matrix
$\hat{f}_{r1}$	Surge-foundation force Fourier coefficients
$\hat{e}_1$	Surge wave-exciting force Fourier coefficients
G_{15}	Surge-pitch wave-radiation convolution integral matrix
γ	Surge-foundation force penalty weight
P_{abs}	Time-averaged absorbed power
C_r	Ratio of power from optimal control to maximum absorption under motion constraints
F_r	Ratio of $\lvert X_{r1}\rvert$ from optimal control to maximum power absorption under motion constraints
L_B, U_B	Penalty weight lower and upper bound
E_w	Cumulative absorbed energy assuming a nondimensional capture width of 1

Subscript	Description
p	Passive absorption from setting $C_g = 0$ and selecting $B_g \geq 0$ that maximizes power
mc	Active absorption from selecting C_g and $B_g \geq 0$ that maximizes power under motion constraints
z	Pitch motion and PTO torque profiles required to eliminate the surge-foundation force
n	Natural (unforced) pitch motion when setting $C_g = B_g = 0$

calculus of variations (Eidsmoen, 1996), model predictive control (Cretel et al., 2011; Abraham and Kerrigan, 2013; Li and Belmont, 2014), and pseudo-spectral methods (Bacelli and Ringwood, 2011 and Herber and Allison, 2013). However, these control strategies focus primarily on maximizing the time-averaged absorbed power without weighing considerations on the corresponding peak forces, torques, and fatigue damage accumulation (Zurkinden et al., 2013). It can be expected that as the controller works to maximize the absorbed