Cairo University

SYSTEM FREQUENCY TUNING FOR HEAVING BUOY WAVE ENERGY CONVERTERS

By

Ahmed Hamdy Abdelmaguid Sakr

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
Mechanical Design and Production Engineering

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
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FACULTY OF ENGINEERING, CAIRO UNIVERSITY
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Title of Thesis:

System Frequency Tuning for Heaving Buoy Wave Energy Converters

Key Words:

Wave energy; Heaving; Buoy; Energy frequency; Reactive loading control

Summary:
In this thesis, we present a quick long-term reactive loading control for heaving buoy wave energy converter. The control is achieved by introducing an external continuous variable stiffness that is connected to the buoy to tune its natural frequency. The external stiffness is connected to the buoy through a continuous V-belt drive to change its effect on the buoy. This control maximizes the oscillation amplitudes; hence, maximizing the power absorption efficiency by achieving near-resonance operation. Analytical results show a promising power absorption increase as compared to other control techniques. Experimental results, for an equivalent vibrating system, prove the concept of the control operation.

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Dedication

This thesis work is dedicated to my wonderful parents who have been a constant source of support and encouragement during the challenges of graduate school and life.

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Nomenclature

Δ	Speed ratio
δ	Kronecker delta function
η	Power absorption efficiency
κ	Convolution kernel
λ	Capture width
λ_{rd}	Multiplication factor with inverse time dimensions
ρ	Density of sea water
ϕ	Taper angle of the sheave
ϕ_i	Random phase for irregular waves modeling
$\psi_e(t)$	Even function of the impulse response function for radiation
$\psi_o(t)$	Odd function of the impulse response function for radiation
$\psi_r(t)$	Impulse response function for radiation
ω	Frequency in (rad/s)
ω_e	Wave energy frequency in (rad/s)
ω_m	Peak frequency in (rad/s)
ω_n	System natural frequency in (rad/s)
ω_{nb}	Heaving buoy natural frequency in (rad/s)
ω_z	Zero-up crossing wave frequency in (rad/s)
$a(\omega)$	Acceleration in frequency domain
$\hat{a}$	Acceleration in complex amplitude
A	Bretschneider formula parameter dependent on the maximum frequency
AR	Amplification ratio
A_b	Heaving buoy cross-sectional area crossing the water surface
A_{ps}	System matrix for the radiation force state space sub-system
A_s	System matrix of the state space model
b	Power take-off system damping

b_{opt}	Power take-off system optimum damping
b_r	hydrodynamic damping
B	Bretschneider formula parameter dependent on the root mean square value of the spectrum
B_{ps}	System vector for the radiation force state space sub-system
B_s	System vector of the state space model
C_p	Central distance between pulleys
C_{ps}	System vector for the radiation force state space sub-system
C_s	System vector of the state space model
d	Heaving buoy draft (submerged height)
D_α	Running diameter of pulley α
$D_{\alpha,min}$	Minimum running diameter for sheave α
D_b	Heaving buoy diameter
D_{pb}	Buoy-side pulley running diameter
D_{ps}	External-spring-side pulley running diameter
E	Energy spectral density function
f_d	Damping force
f_e	Excitation force
f_r	Radiation force
f_s	Restoring force
f_t	Tuning force
$\hat{F}_e$	Heave excitation force complex amplitude
$\hat{F}_r$	Radiation force complex amplitude
g	Gravitational acceleration
h	Water depth
$H_0^{(1)}$	Hankel function of first kind of order 0
$H_0^{\prime(1)}$	First derivative of Hankel function of first kind of order 0
$H_{1/3}$	Average wave height of the highest one-third waves

H_s	Significant wave height
i	Complex number
I_0	The first derivative of the modified Bessel function of the first kind of order 0
$\acute{I}_0$	Modified Bessel function of the first kind of order 0
I_1	Modified Bessel function of the first kind of order 1
I_p	Moment of inertia of the pulleys
J_0	First Bessel function of order zero
$J_0^{'}$	First derivative of first Bessel function of order zero
k	Stiffness of the system
k_0	Modified Bessel function of the second kind of order 0
$\acute{k}_0$	First derivative of modified Bessel function of the second kind of order 0
k_b	Heaving buoy buoyancy stiffness
$k_{controller}$	Controller variable external stiffness
k_{eff}	System effective stiffness
k_{ext}	External stiffness
L_p	V-belt pitch length
m_0	Zeroth spectral moment
m_2	Second spectral moment
m_b	Heaving buoy mass
m_{eq}	Equivalent oscillating mass of the moving components of the controller
m_n	n_{th} spectral moment
m_r	hydrodynamic added mass
m_{tot}	Total oscillating mass including the controller inertia effect
P	Available power per unit width of wave front (power flux)
P_{av}	Average absorbed power
P_k	Kinetic power
P_m	Power consumed in the mechanical damper
$P_{m,max}$	Maximum power consumed in the mechanical damper