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Dynamic analysis of wave energy converter by incorporating the effect of hydraulic transmission lines

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ABSTRACT

A heaving-buoy wave energy converter equipped with hydraulic power take-off is studied in this paper. This wave energy converter system is divided into five subsystems: a heaving buoy, hydraulic pump, pipelines, non-return check valves and a hydraulic motor combined with an electric generator. A dynamic model was developed by considering the interactions between the subsystems in a state space form. The transient pressures caused by starting/stopping the buoy or closing/opening the check valves were predicted numerically using the established model. The simulation results show that transmission line dynamics play a dominant role in the studied wave energy converter system. The length of the pipeline will not only affect the amplitude of the transient pressures but also affect the converted power. The variation of the time-averaged converted electric power with the pipeline length is estimated using the simulation method for the buoy exposed to one irregular sea state. Finally, it is suggested how reduced power efficiency due to the pipelines may be ameliorated.

1. Introduction

In this paper, a heaving buoy, moving relative to a fixed reference, equipped with a hydraulic power take-off machinery, are studied (Fig. 1). For this wave energy converter system, the oscillating motion of the buoy is converted into the flow of a liquid at high pressure with a hydraulic pump. The fluid is then pumped into a high-pressure accumulator for short-term storage. A hydraulic motor uses this high-pressure fluid from the accumulator to drive an electric generator. During the operation, the fluid is prevented from being pumped from the cylinder into the low-pressure accumulator or being sucked from the high-pressure accumulator into the cylinder with self-acting check valves.

The performance of this type of wave energy converter system was first studied by Falcão (2007). In his study, the hydraulic machinery force acting on the buoy was simplified as a Coulomb damping force, and time-domain analysis was used to evaluate the converted electric power in irregular waves. Later, Yang et al. (2010) developed a dynamic model for a same wave energy converter configuration using a state space formulation. In their work, the fluid compressibility in the hydraulic pump was taken into account. The piston ring and cylinder bore wear damage was studied numerically using their developed mathematic model. A series of studies of hydraulic power take-off in different wave energy converter models have been conducted by Eidsmoen (1995), Bjarte-Larsson and Falnes (2006), Hals et al. (2007), Yang et al. (2009) and others. However, in the aforementioned studies, the pipelines were either neglected or included as an equivalent dissipative component. The transient flow problems in the pipeline have not yet been addressed in a wave energy converter system.

The hydraulic pipelines play a significant role in achieving the desired energy conversion efficiency and durability of a wave energy converter system. In the design of pipeline, both normal operating pressures as well as transient pressures need to be considered. The transient pressures accompany any change in the rate of fluid flow in the pipeline, such as the start/stop of the buoy or closing/opening of a valve (Wylie et al., 1993). The induced pressure pulsations (water hammer) in the pipeline are a source of noise and vibration and may significantly influence the reliability or performance of the wave energy converter system. Consequently, it is highly desirable to be able to predict pressure pulsations at the design stage of a wave energy converter system so that appropriate steps may be taken to minimize their levels and their influence.

Pipeline dynamics have been studied extensively since the 1950s. Considerable efforts have been made by many authors to develop the transient models both in the frequency domain (e.g., Karam and Franke, 1967) and the time domain (e.g., Tsao, 1968). The pipeline model in the frequency domain can characterize the fluid transients for the pipelines connected to a linear system well. However, if the system is nonlinear, as in the wave energy

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Nomenclature

α	piston area ratio
β	bulk modulus
ρ	fluid density
$\Gamma(s)$	propagation operator
ω	frequency
ω_c	viscosity frequency
ω_m	angular speed of the shaft
ξ	position ratio of valve
γ	ratio of specific heat
τ	torque acted on the shaft
υ_0	kinetic viscosity of fluid
Φ	resisting force
Ω	open area ratio of valve
a	acoustic velocity
A_∞	added mass at infinite frequency
A_w	water plane area of the buoy
$\mathbf{A},\mathbf{B},\mathbf{C}$	state space coefficients
B	fluid friction coefficient
D	diameter
D_m	motor displacement
D_n	dissipation number
F	force
H_s	significant wave height
J	shaft inertia moment
$K(t)$	retardation function
K	stiffness
L	cylinder half length
m	buoy mass
$\mathbf{M}$	transfer function at steady state
P	pressure
Q	fluid flow rate
R	radius
s	Laplace operator
S	hydrostatic stiffness
t	time
$\mathbf{T}$	transfer function matrix
T_c	dimensionless closure time
T_p	spectral peak wave period
T_r	returned period
w	attenuation factor
u	flow velocity in the pipe
V	volume
x	stem position of valve
X	position coordinate
$\mathbf{z}$	additional state space vector
Z_0	line impedance constant
$Z_c(s)$	line characteristic impedance

Subscripts

0	initial or default value
A,B	upper, lower chambers
c	closure
cyl	hydraulic cylinder
$down$	downstream side
end	end-stopper
exc	excitation force
ext	external force
f	friction
$fluid$	working fluid in the system
g	generator
hm	hydraulic motor
HP	high pressure accumulator
$I1$, $I2$	inlet check valves
le/li	external/internal leakage
LP	low pressure accumulator
n	natural frequency
nor	normalized variable
$O1$, $O2$	outlet check valves
p	piston
pl	pipeline
r	rod
ss	steady state condition
$tran$	transient pressure
up	upstream side
val	check valves
$wave$	incident wave

converter system studied in this paper, frequency domain analysis is not valid. In this case, time domain solutions are desirable.

The method of characteristics is a simple and accurate method for transmission line transient analysis (Wylie et al., 1993) in the time domain. The disadvantage of this method is that it is based on a fixed discretization in the time–distance plane. It is not easy to incorporate the model into a coupled simulation system with variable time steps (Mäkinen et al., 2000). To avoid the weakness of a numerical solution, modal approximation methods based on the infinite product representation of a hyperbolic transfer function (Oldenburger and Goodson, 1964) were developed (Hsue and Hullender, 1983, Yang and Tobler, 1991). This approximation model can be represented in a linear state space form that can be added directly to Ordinary-Differential-Equation (ODE)-based simulation systems. To take advantage of this method, a modal approximation method of the pipeline is employed in this paper.

The non-return check valves connected to the pipelines are dynamic boundaries during their actuation (i.e., they are opening or closing) and represent one of the main causes of fluid transients. To compute pressure transients due to valve closures, Wood and Jones (1973) generated a series of charts that give the water-hammer pressure for a wide variety of initial conditions and closure times for several standard valve configurations. However, the dynamic characteristics of the valves were not included in their study. Johnston (1991) developed a dynamic model for a spring-loaded check valve to study the performance of reciprocating pumps. Later, Shu et al. (1997) studied the pressure pulsations in reciprocating pump systems by incorporating the transmission line model and the dynamic valve model given by Johnston (1991). In practice, there are many types of valves. Each valve has its own dynamic characteristics and models. In this paper, a spring-loaded valve was chosen to illustrate the transient pressure phenomenon.

As mentioned above, although the transient pressure in a hydraulic system has been studied extensively in the past, according to the author's knowledge, integrated analysis of wave energy converters do not appear to have been addressed. The wave energy converter system considered herein consists of several subsystems: floating buoy, hydraulic pump, transmission lines, check valves, hydraulic motor and electric generator. The models of the subsystems are based on basic physical laws and are described in different publications. To obtain insight into the various subsystems that play a role in the behavior of the wave energy converter system, an integrated model is desirable. The main purpose of this paper is to integrate the fundamental