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Nonlinear dynamics of a tightly moored point-absorber wave energy converter

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ABSTRACT

Tightly moored single-body floating devices are an important class of offshore wave energy converters. Examples are the devices under development at the University of Uppsala, Sweden, and Oregon State University, USA, prototypes of which were recently tested. These devices are equipped with a linear electrical generator. The mooring system consists of a cable that is kept tight by a spring or equivalent device. This cable also prevents the buoy from drifting away by providing a horizontal restoring force.

The horizontal and (to a lesser extent) the vertical restoring forces are nonlinear functions of the horizontal and vertical displacements of the buoy, which makes the system a nonlinear one (even if the spring and damper are linear), whose modelling requires a time-domain analysis. Such an analysis is presented, preceded, for comparison purposes, by a simpler frequency-domain approach. Numerical results (motions and absorbed power) are shown for a system consisting of a hemispherical buoy in regular and irregular waves and a tight mooring cable. The power take-off is modelled by a simplified system of a linear spring and a linear damper and also by a system formed by a hydraulic piston and spring. Different scenarios are analysed.

1. Introduction

Floating oscillating-body devices are a large class of wave energy converters (WECs) for deployment offshore, typically in water depths between 40 and 100 m (Falcão and de, 2010). Among these, the simplest device is the single body reacting against the sea bottom. An early example is the Norwegian buoy, consisting of a spherical floater which could perform heaving oscillations relative to a strut connected to an anchor on the sea bed through a universal joint (Budal et al., 1982). A model (buoy diameter = 1 m) was tested (including latching control) in the Trondheim Fjord in 1983.

An alternative design is a buoy connected to a bottom-fixed structure by a cable which is kept tight by a spring or similar device. The motion of the wave-actuated float on the sea surface activates a power take-off (PTO) system. Such a device was investigated in Norway in the late 1970s (Falnes and Budal, 1978; Budal and Falnes, 1980), but later abandoned (Falnes and Lillebekken, 2003). In the device that was tested in Denmark in the 1990s, the PTO (housed in a bottom-fixed structure) consisted in a piston pump supplying high-pressure water to a hydraulic turbine (Nielsen and Smed, 1998).

The taut-moored buoy being developed at Uppsala University, Sweden uses a linear electrical generator (rather than a piston pump) placed on the ocean floor (Waters et al., 2007). A line from the top of the generator translator is connected to a buoy located at the ocean surface, and in this way acts as a PTO transmission line. Springs attached to the translator bottom, store energy during half a wave cycle and simultaneously act as a restoring force in the wave troughs. Sea tests off the western coast of Sweden of a 3 m diameter cylindrical buoy are reported in Waters et al. (2007).

Another system with a heaving buoy driving a linear electrical generator was recently developed at Oregon State University, USA (Elwood et al., 2009). It consists of a deep-draught spar and an annular saucer-shaped buoy. The spar is taut-moored to the sea bed by a cable. The buoy is free to heave relative to the spar, but is constrained in all other degrees of freedom by a linear bearing system. The forces imposed on the spar by the relative velocity of the two bodies is converted into electricity by a permanent magnet linear generator. The spar is designed to provide sufficient buoyancy to resist the generator force in the down direction. A 10 kW prototype was deployed off Newport, Oregon, in September 2008, and tested (Elwood et al., 2009).

The mooring system in these devices consists of a cable, that connects the buoy to a sea-bottom-fixed structure and that is kept tight by a spring or equivalent device, or, alternately (as in the Norwegian buoy) is a strut connected to the sea bed by a universal joint.

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Nomenclature

a	radius of floater
A	added mass
A_w	wave amplitude
B	radiation damping coefficient
C	damping coefficient for the linear PTO
f	PTO force
f_d	diffraction or excitation force
F	pre-tension(linear PTO)or piston force (hydraulic PTO)
F_M	spring force in the hydraulic PTO system
F_P	piston force in the hydraulic PTO system
g	acceleration of gravity
L	initial cable length
H_s	significant height of irregular waves
K	stiffness of the mooring line
m	mass of floater
n	nth harmonic in irregular waves
N	number of harmonics in irregular waves
P	power
$\overline{P}$	time-averaged power
PTO	power take-off mechanism
ΔL	cable length variation
S	πa^2
$S_\varsigma(\omega)$	power spectral distribution
t	time
T_e	energy period of irregular waves
U	complex amplitude of velocity
X, z	displacements of body centre (Fig. 1)
X, Z	complex amplitudes of body centre displacement
α	angle between the mooring cable and vertical direction
θ	irregular wave harmonic phase
Γ	excitation force coefficients
ϕ	mooring cable force
ρ	density
ω	radian frequency

Subscripts

irr	irregular wave
x, z	directions of x, z axes

Superscript

*	dimensionless value

Some studies have already been made on the dynamics of a taut-moored buoy (all or most of which without any type of energy conversion) in a fluid flow or in waves. Some early initial results in a theoretical and experimental analysis (Harleman and Shapiro, 1960) of the dynamics of a single-moored hemispherical buoy in shallow water indicated that the sphere motion and mooring line forces were related to the sphere size, weight, submergence and also to the wave frequency, wave height and water depth. Also, some numerical simulations on the motion of buoys in different wave climates (Carpenter et al., 1995), later supported by experimental results, indicated that the surge response of a spherical buoy was highly dependent on the system natural oscillation frequency. The effects of floaters geometry on the hydrodynamics and performance of a tightly moored floating single-body WEC was studied by Mavrakos et al. (2009).

The work here presented focuses on the nonlinear dynamics introduced by the mooring system of these wave energy converters and on the analysis of the influence of the mooring

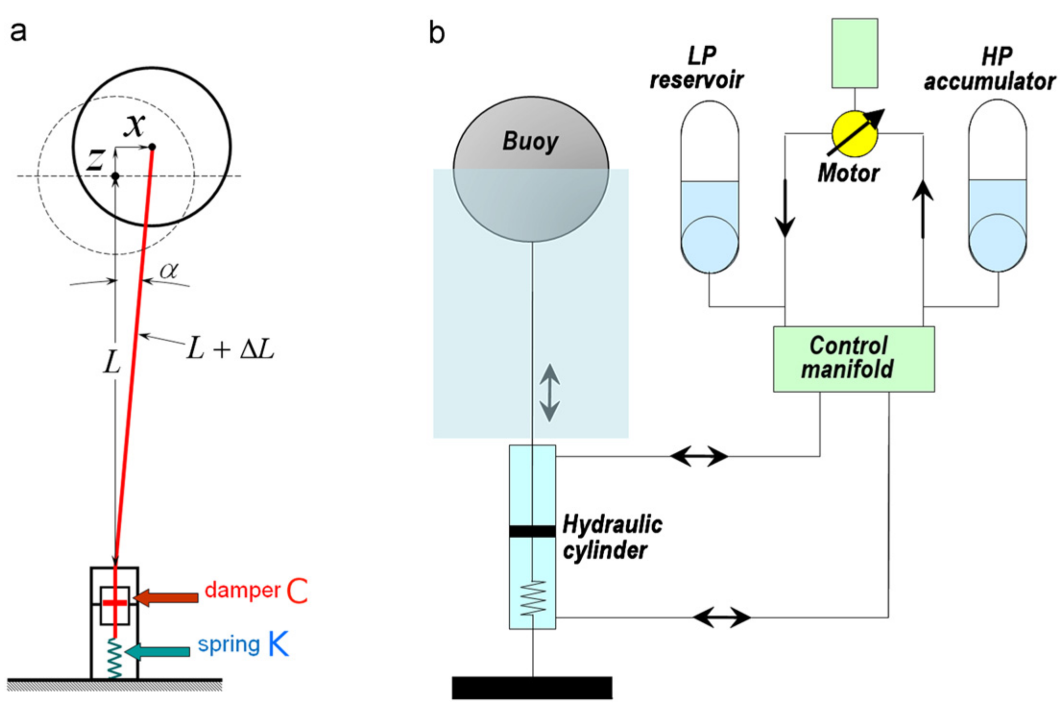

Fig. 1. Buoy, PTO and mooring line: (a) Linear PTO model, (b) Hydraulic PTO model.