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Modal analysis of a submerged spherical point absorber with asymmetric mass distribution

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ABSTRACT

Of all the wave energy converter (WEC) categories, the single-tether point absorber (PA) is one of the most widely used in the ocean renewable energy industry. In most published research, only the heave motion of the buoy is considered in the motion equation for the analysis. This is because the heave motion of the buoy strongly couples to the power take-off device (PTO), whereas the surge and pitch motions barely couple to the PTO. As a result, only the power arising from heave motion of the buoy can be efficiently absorbed when a single-tether PTO is used, leading to deficiency of the design in absorbing the power arising from its surge and pitch motion. In this paper, the deficiencies of single-tether PAs are addressed by simply shifting the center of gravity of the buoy away from its geometric centre. A spherical buoy with asymmetric mass is used in this paper for its simplicity. The asymmetric mass distribution of the buoy causes motion coupling across surge, heave and pitch motions, which enables strong coupling between the buoy's surge motion and the PTO movement. The operation principle and power generation of the spherical point absorber with asymmetric mass distribution (SPAMD) are investigated via a modal analysis conducted on a validated frequency-domain model. The results show that the SPAMD can be up to 3 times more efficient than the generic PAs when subjected to regular waves in the frequency range from 0.34 rad/sec to 1.4 rad/sec.

1. Introduction

Since the Oil Crisis of the 1970s, ocean wave energy has been regarded as a potential source of renewable power. Compared with solar and wind, the power carried by ocean waves is more continuous and predictable. However, it is difficult to extract the energy from the reciprocating ocean wave motion efficiently by using conventional electricity generators. Consequently, commercial-scale wave energy conversion still does not exist.

The single-tether point absorber (PA) is one wave energy converter (WEC) that has commercial potential and has received significant attention from the research community. In most published work, single-tether PAs are typically modelled as single degree-of-freedom (DOF) heaving devices, even though in reality the devices move in multiple DOFs (e.g. surge, heave and pitch). This is because, for single-tether PAs, the heave motion of the buoy strongly couples to the power take-off device (PTO) and therefore this motion can be fully converted to the PTO extension. In contrast, the surge and pitch motions barely couple to the PTO and only a tiny fraction of these motions are converted to useful energy. Fig. 1 illustrates the contribution of the PTO extension from pure heave and surge motions respectively for a single-tether PA. It is clear that the heave displacement of the buoy results in an equivalent PTO extension, whereas the surge displacement leads to negligible PTO extension. Therefore, for single-tether PAs, only the heave motion can result in effective power absorption.

Considering the theoretical capture width of a 3DOF (i.e., surge, heave and pitch) PA can be three times greater than a heave-only PA [1], several conceptual designs have been proposed to maximize the absorption efficiency of the PA by harvesting the energy arising from its surge and pitch motions. One typical solution is to attach multiple PTO tethers to the buoy, which couple to the orthogonal degrees of freedom. It has been shown that a three-cable PTO [2] is capable of absorbing three times more power than a single-tether heaving PA over a broad frequency range [3], at the expense of increased captial cost from two additional PTOs and mooring points. A similar solution is to use two decoupled PTOs in alignment with the heave and pitch directions to capture more wave energy

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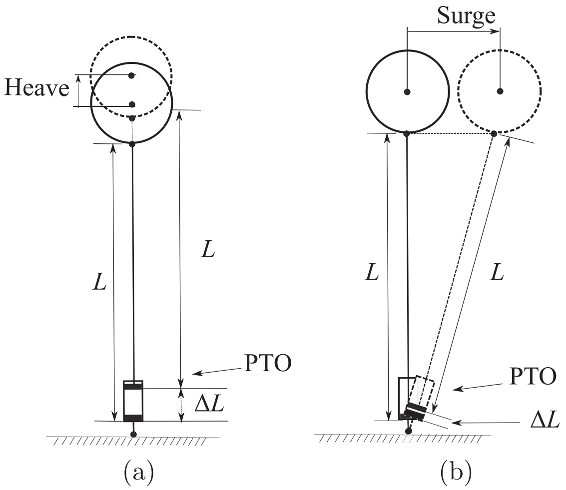

Fig. 1. Comparison of the PTO extension caused by the heave and surge motions of the buoy: (a) the heave displacement is fully converted to the PTO extension; (b) only a tiny fraction of the surge displacement is converted to the PTO extension. L is the nominal tether length when the buoy is at equilibrium, ΔL is the tether length change.

[4]. The theoretical capture width of this approach is equivalent to that of the PA with a three-cable PTO. However, the PA with two decoupled PTOs is sensitive to wave direction, since the PTO must be aligned to the incoming wavefront.

In this paper, a more effective solution that allows a single-tether PA to harvest energy arising from surge motion of a submerged spherical buoy is proposed. The approach is based on simply offsetting the mass from the centre of the buoy, such that when the buoy is excited in surge, heave motion is also enhanced. A submerged 3DOF (i.e., surge, heave and pitch) PA is employed because it can more efficiently use the surge motion to capture wave energy than an equivalent floating device [5]. It should be noted that although there are some prototypes (e.g. Salter's Duck [6] and the parametric pendulum based wave energy converter [7]) which use an asymmetric mass buoy to harvest wave energy, this is the first study which utilises the motion coupling caused by the asymmetric mass distribution to address the poor PTO coupling of a single-tether PA in surge motion. In Section 2, the system of spherical point absorber with asymmetric mass distribution (SPAMD) is described, with the settings of operating environment, the asymmetric mass buoy and the PTO clarified. In Section 3, the static stability condition of the SPAMD is investigated. Furthermore, the equations of motion are derived in the frequency domain for the subsequent modal analysis. In Section 4, the methodology for analysing the oscillation modes and assessing the power output of the SPAMD are presented. In Section 5, a modal analysis is presented, with the aim of understanding the operation principles of the SPAMD and evaluating its power generation capability. The paper is concluded in Section 6.

2. System description

For simplicity, a submerged spherical asymmetric mass buoy with a positive buoyancy is considered in this work. The buoy is tethered by a linear spring-damper PTO to be immersed below the free water surface. The PTO is anchored to the sea bottom via a ball-joint which allows the PTO to align with the mooring tether under tension when the buoy is excited by incident waves. The tether is assumed to be non-elastic and massless. The incident waves are set to be linear monochromatic waves aligned with the vertical XZ-plane of the Cartesian space, propagating along the positive X-axis, as shown in Fig. 2. As the SPAMD is designed to be symmetric about the XZ-plane, it is assumed that the buoy only moves in the plane with surge, heave and pitch motion when excited by the plane waves.

The detailed descriptions of the operating environment, the asymmetric mass buoy, and the PTO are presented below.

2.1. Operating environment

The SPAMD operates in a finite depth water column. In this paper, the water depth is assumed to be 60 m. The submergence depth of the buoy is 3 m from top of the buoy to the sea surface, chosen as a compromise between maximum hydrodynamic coefficients and mitigating surface piercing. The frequency of incident monochromatic waves ranges from 0.34 rad/sec to 1.4 rad/sec, covering the major wave frequencies off the Australian coasts [8]. The wave amplitude was set to 0.1 m, which is sufficiently small to meet the linear wave assumption and small displacement assumption used in the modelling. It should be noted that an increase in wave amplitude above 0.1 m compromises the linear wave assumption and leads to an increase in viscous drag and kinematic non-linearities. Fig. 3 shows the hydrodynamic coefficients for the defined operating environment [9].

2.2. Asymmetric mass buoy configuration

Fig. 4 shows the free-body diagram of SPAMD buoy in the vertical XZ-plane in the Cartesian space. The buoy coordinates are defined in a body-fixed frame with an origin located at the centre of the buoy. The SPAMD buoy consists of a spherical hull with a smooth surface of mass m_1, and an additional mass of m_2 offset from the centre of the buoy on the XZ-plane. The total mass is $m = m_1 + m_2$.

The buoy is assumed to be formed from a hollow spherical buoy of radius r. The mass of the hollow spherical body can be simplified as a point mass, m_1, located at the geometric centre of the body, with a moment of inertia about the centre of the buoy, $I_1 = \frac{2}{3} m_1 r^2$.

The offset mass, m_2, is formed by the intersection of a plane with the spherical buoy and is attached on the inner surface of the spherical hull. Its centre of gravity is offset from the centre of the buoy by an offset distance, r_{gy}, and an offset angle, φ. The angle φ is measured from the positive X-axis to the offset mass, as shown in Fig. 4. The centre of the gravity of the offset mass is denoted as (x_2, z_2). In the subsequent modelling in Section 3, the offset mass m_2 can be simplified as an offset point mass m_2, with the moment of inertia about the centre of the buoy $I_2 = m_2 r_{gy}^2$.

In this work, the mass distribution of the SPAMD is determined by the weight-to-buoyancy ratio, δ, the mass ratio, m_1/m_2 and the mass-offset position, defined by the mass offset radius r_{gy} and mass offset angle φ. Noting that the behavior of the SPAMD is affected by the weight-to-buoyancy ratio, mass ratio and mass-offset position, which might be considered as tuning parameters. Table 1 lists the buoy's parameters used in the analysis. The weight-to-buoyancy ratio is set to 0.5, and the mass ratio to 1. The radius of the buoy is 5 m, to be consistent with previous research on point absorbers [5]. It has been assumed that the mass offset radius, r_{gy}, is 4.5 m. In this study, the offset angle φ is set to be 30 deg, which means the offset mass m_2 is below the centre of the buoy. The values of the weight-to-buoyancy ratio, mass ratio and mass-offset position were chosen from an unpublished optimisation study on the SPAMD.

Since the offset mass, m_2, causes an additional moment at the centre of the buoy, the tether attachment point on the buoy needs to be adjusted to the opposite side of the buoy to maintain the static