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A time-domain simulator for an oscillating water column in irregular waves at model scale

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ABSTRACT

This paper presents a 1D time-domain model for an oscillating water column (OWC) based on previous works on trapped air cavities for marine vehicles. The paper describes the coupling between the hydrodynamic and the thermodynamic forces for an OWC with an orifice. The model enables to obtain the water elevation and pressure variation inside the chamber in the time-domain for regular and irregular waves. The numerical predictions are compared with experimental data performed on a model scale OWC.

1. Introduction

The oscillating water column (OWC) has been the object of a lot of past work. Many numerical models have been developed using potential theory (Josset and Clément, 2007), based on a radiation and a diffraction approach, or computational fluid dynamic (CFD). However, these models require a lot of modeling effort as a mesh is required.

This paper presents a different approach based on the work on trapped air cavities for marine vehicles (also known as motion control tanks) to enhance the wave-induced motion through pneumatic compliance (Harrisson et al., 1987; Patel and Harrison, 1986; Patel, 1987; Patel and Witz, 1987a,b). This is achieved with open bottom tanks partly submerged and with a trapped volume of air above the internal waterline. Wave action induces variation of the internal water level and therefore of the internal pressure. An OWC is similar to one of these trapped air cavities except that a turbine is fitted at the orifice in order to retrieve energy out of the pressure drop between the internal pressure and the atmospheric pressure (see Fig. 1).

This paper describes the coupling between the hydrodynamic and thermodynamic problems which governs the water elevation as well as the pressure variation in the chamber when the device is subjected to regular and irregular waves. Furthermore, the theoretical predictions are compared with experimental data from tank testing.

Note that the distinction between "OWC" and "water column" is made throughout the paper to distinguish the actual chamber from the oscillating column of water.

2. Mathematical model

2.1. Assumptions

Some assumptions are made in the mathematical model presented here. First, the water column is assumed to be a solid vertical cylinder, with a mass equal to the cylinder of water from the bottom of the chamber to the internal water level.

The wave field is normally affected by the structure and diffraction forces should be taken into account. However, in this model, diffraction is ignored.

In addition, turbulence effects which may occur inside the chamber or vortex shedding at the edge of the walls of the buoy are not considered as well as viscous effects along the wetted area of the chamber.

Finally, the added mass and damping coefficient of the water column are assumed to be frequency independent.

Only waves with small amplitude are considered and linear theory is used. Therefore, the principle of superposition can be applied here.

2.2. Hydrodynamic problem

This section presents the derivation of the governing equation for the water elevation inside an OWC subjected to regular and irregular waves.

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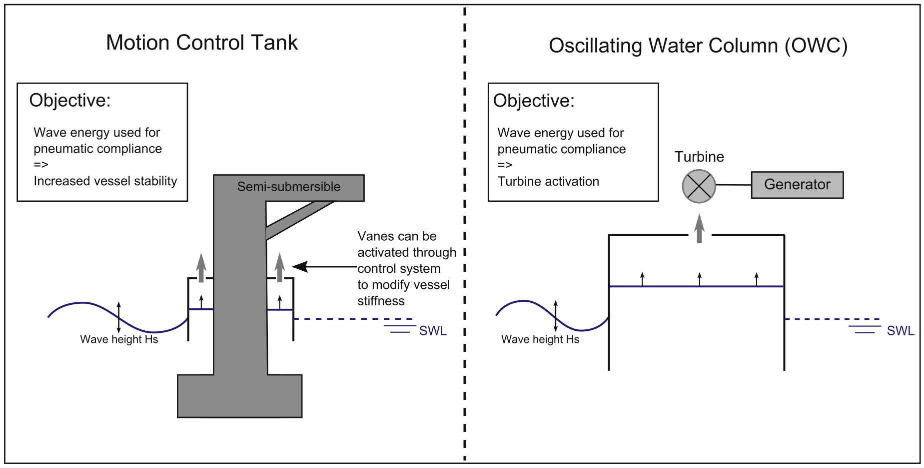

Fig. 1. Analogy between the motion control tank system and an OWC.

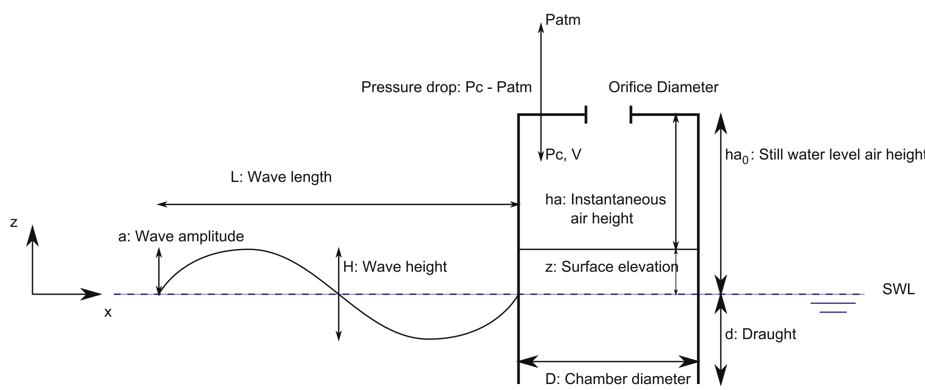

Fig. 2. Schematic representation of an OWC.

Considering the internal volume of water contained in the chamber, the Z-axis is fixed at the mean still water level. Let z be the internal water elevation in the chamber. Fig. 2 presents a schematic representation of an OWC.

Newton's second law applied to the internal volume of water in the Z-direction yields to the equation of motion in heave:

$$M\ddot{z}+B\dot{z}+Cz=F(t) \quad (1)$$

where M is the mass of the column of water, B the damping coefficient, C the hydrostatic restoring coefficient and $F(t)$ the total force acting on the water column.

The damping coefficient is assumed to be a function of the mass, added mass and hydrostatic restoring coefficient assumed to be 10% of critical (Patel and Harrison, 1986). Thus, if R denotes the radius of the water column, the coefficients M, B and C are defined as

$$\begin{cases} M=\rho\pi R^2\cdot(d+z) \\ B=0.2\cdot\sqrt{C(M+M_a)} \\ C=\rho g\pi R^2 \end{cases} \quad (2)$$

where M_a is the added mass in the vertical direction for a vertical cylinder and is assumed to be equal to that of a hemisphere of equal radius, $M_a=\frac{2}{3}\rho\pi R^3$ (Patel and Harrison, 1986). The total force acting on the water column includes the added mass force $F_a(t)$, the Froude–Krylov force $F_{FK}(t)$ at the bottom and the vertical force due to the varying air pressure inside the chamber $F_{\delta P_{air}}(t)$.

Thus, the excitation force can be expressed as

$$F(t)=F_a(t)+F_{FK}(t)+F_{\delta P_{air}}(t) \quad (3)$$

The air force on the water column is given by

$$F_{\delta P_{air}}(t)=-\Delta P(t)\cdot\pi R^2 \quad (4)$$

where ΔP is the difference between the inner pressure and the atmospheric pressure. The governing equation for ΔP is derived in the next section. General expressions for $F_a(t)$ and $F_{FK}(t)$ are

$$F_a(t)=M_a\cdot(\dot{w}-\ddot{z}) \quad (5)$$

$$F_{FK}(t)=P_{wave}(t)\cdot\pi R^2 \quad (6)$$

where $\dot{w}-\ddot{z}$ is the relative vertical acceleration of the water column to the fluid and $P_{wave}(t)$ the wave hydrodynamic pressure at the bottom of the water column. Both of these quantities are given by linear wave theory. Let us consider a regular wave of angular frequency ω_i, amplitude a_i and phase ϕ_i. If the wave elevation is defined as $\eta_i(t)=a_i\cdot\cos(\omega_i t+\phi_i)$, according to the linear wave theory, the vertical particle velocity and acceleration at arbitrary depth z are given by

$$\begin{cases} w_i=-\omega_i a_i\cdot\dfrac{\sinh k_i(z+h)}{\sinh k_i h}\cdot\sin(\omega_i t+\phi_i) \\ \dot{w}_i=-\omega_i^2 a_i\cdot\dfrac{\sinh k_i(z+h)}{\sinh k_i h}\cdot\cos(\omega_i t+\phi_i) \end{cases} \quad (7)$$