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Heave motion response of a circular cylinder with the dual damping plates

Hyeok-Jun Koh [a], Il-Hyoung Cho [b,*]

[a] Marine & Offshore Engineering Division, Zentech E&C Co., Ltd., Seoul, Republic of Korea
[b] Department of Ocean System Engineering, Jeju National University, Jeju, Republic of Korea

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ABSTRACT

A damping plate attached to the floating structure has a distinct advantage in reducing the motion response of a floating structure by increasing the added mass and damping. Analytical and experimental studies were carried out to investigate the heave motion response of a floating cylinder according to the characteristics of dual damping plates (DDPs), such as submergence depth and radius ratio. An analytical method using a Matched Eigenfunction Expansion Method (MEEM) was developed for solving the radiation problem by a heaving circular cylinder with DDPs in the context of linear potential theory. To confirm the present analytical solutions, a series of experiments for heave motion responses was conducted in a two-dimensional wave tank in regular waves with varying wave frequencies. The analytical results were in good agreement with the experimental results, and the heave motion response of the cylinder was decreased considerably within the region of heave resonance frequency by installation of the proposed DDPs. By using the predictive tools requiring less calculation time, the effect of damping plates as motion reduction devices for spar-type offshore platforms can be assessed for various combinations of parameters such as the number, size, and location of damping plates at the concept design stage.

1. Introduction

An excessive heave motion is the result of a resonance that is generated when the natural frequency of the floating structure and the frequency of incident waves coincide. It can often cause severe damage in risers or mooring systems of offshore platforms. The basic concept of reducing the motion response of a floating body is to increase the damping energy of the system by increasing the radiation and viscous damping, or to move the natural frequency of the structure out of the dominant frequency range of the incident waves by increasing added mass. An appendage that adheres to the structure for the purpose of reducing the motion of the floating structure is referred to as a damping plate.

An analysis of hydrodynamic forces by the motion of a floating structure has been carried out by many researchers. Havelock (1955) analyzed the added mass and damping coefficient of a sphere floating on a free surface using a multipole expansion method. Mei and Black (1969) solved the radiation problem and diffraction problem of a two-dimensional floating square structure. The scattering problem of a cylinder was dealt with by Garrett (1971) and the radiation problem was analyzed by Tung (1979) and McIver and Evans (1984). In addition, Kritis (1979) applied the hybrid method of Yeung (1975) to an axisymmetric body and gave numerical results for a circular cylinder. Yeung (1981) gave the added mass and damping of a vertical cylinder in finite-depth waters.

Furthermore, many studies have been carried out for a circular damping plate that is attached to the cylinder-type substructure. Thiagarajan and Troesch (1998) observed the flow around the cylinder with a damping plate using the particle image velocimetry (PIV) technique. Rho and Choi (2002) carried out model tests to investigate the heave and pitch motion characteristics with a moon pool, strakes and a damping plate of a spar platform. They also confirmed Mathieu-type instability, which occurs when the pitch natural period is twice the heave natural period. Tao and Cai (2004) investigated the vortex shedding pattern and hydrodynamic forces arising from the flow separation and vortex shedding around a damping plate of a circular cylinder by solving the Navier-Stokes equation. Tao et al. (2007) calculated viscous flow by a spar hull with two solid damping plates of variable spacing using a finite difference method. The results showed that a significant influence of the spacing of the plates on the hydrodynamic forces was revealed clearly when it was smaller than the critical value. Molin (2001) proposed a theoretical model to derive the added mass and damping of periodic arrays of perforated disks in unbounded fluid domain. Molin and Nielsen (2004) also investigated the added mass and damping of single perforated disk below the free surface using the discharge equation that relates the pressure drop and relative fluid velocity through the porous disk.

* Corresponding author.
E-mail address: cho0904@jejunu.ac.kr (I.-H. Cho).

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Koh and Cho (2011) analyzed the hydrodynamic forces (added mass and damping coefficient) acting on a cylinder with a damping plate using the Matched Eigenfunction Expansion Method (MEEM). Sudhakar and Nallayarasu (2013, 2014) investigated the influence of single and double damping plates on the hydrodynamic response of a spar in regular and irregular waves by experimental studies.

In this study, the heave motion response of the cylinder was examined according to the variation of the characteristics of the DDPs by means of the MEEM. In the MEEM calculation, the fluid domain is divided into four regions, and the velocity potentials in each region are expressed by the Fourier-Bessel series. The unknown coefficients in each region are determined by applying the continuity of pressure and normal velocity at the matching boundaries. The viscous damping is estimated from free decay test by determining the ratio between successive amplitudes obtained from the decaying oscillation in still water. Additionally, a verification was done for all analytical solutions through a model test in regular waves. It was found that significant increases in the viscous damping by attaching the DDPs lead to a considerable reduction of the heave amplitude and a shift of the resonant frequency to the low frequency region due to the increase in the added mass. In particular, the closer distance between the upper and bottom damping plate, increased the heave motion even more than a cylinder with a single damping plate.

2. Mathematical formulation

We consider the radiation problem of a circular cylinder attached with the DDPs in a water depth h. The radius of the cylinder is assumed to be b and the draft to be d. The damping plates with radius a are attached at the bottom and a depth of $d_0(d_0 < d)$. For the analysis, the polar coordinate system (r, θ, z) is chosen with the origin on the undisturbed free surface and the z-axis pointing vertically upwards. The distance between the bottom of the cylinder and seabed is denoted by $c = h - d$, and the space of the plate by $c_0 = d - d_0$. It is assumed that the fluid is incompressible and inviscid, and the motion amplitudes and velocities are small enough so that linear potential theory can be used. Assuming the harmonic motion of the frequency ω, the velocity potential of the heave motion can be written as $\Phi(r, \theta, z, t) = \mathrm{Re}\{-i\omega\xi\phi(r, z)\, e^{-i\omega t}\}$, where ξ represents the complex displacement of the forced heave oscillation. Because the body is axisymmetric, the radiation potential is a function of r and z.

To apply the MEEM, the fluid domain is divided into four regions (Fig. 1): i.e. (I) the outer region$(r \ge a,\ -h \le z \le 0)$, (II) the upper inner region of the damping plate $(b \le r \le a,\ -d_0 \le z \le 0)$, (III) the mid inner region between plates $(b \le r \le a,\ -d \le z \le -d_0)$, and (IV) the lower inner region of the bottom damping plate $(0 \le r \le a,\ -h \le z \le -d)$.

In the outer region, the velocity potential satisfying the Laplace equation and boundary conditions (free surface, sea bed, and radiation) can be written as:

$$\phi^{(I)}(r, z) = \sum_{n=0}^{\infty} A_n \frac{K_0(k_{1n}r)}{K_0(k_{1n}a)} f_{1n}(z), \tag{1}$$

where K_0 is the modified Bessel functions of the second kind. The eigenvalues k_{1n} are the solution of the following dispersion equation.

$$k_{1n}\ \tan\ k_{1n}h = -\frac{\omega^2}{g}, \quad n = 0, 1, 2, \cdots \tag{2}$$

where $n = 0(k_{10} = -ik_1)$ term corresponds to an outgoing waves

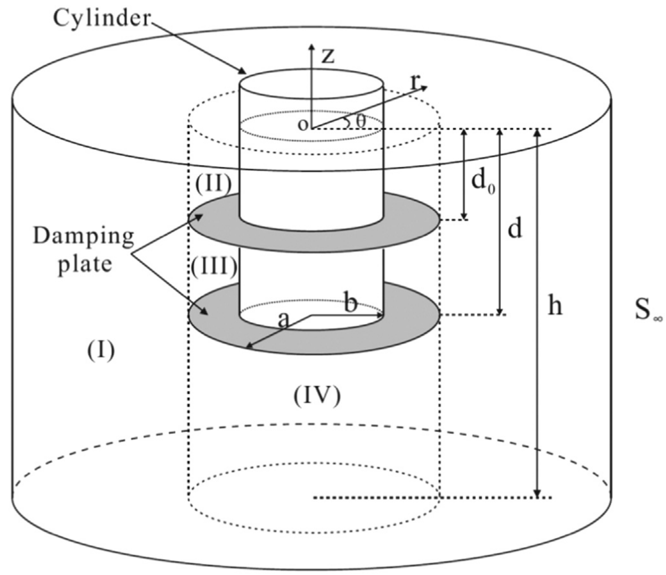

Fig. 1. Definition sketch of a circular cylinder with the DDPs.

and $n \ge 1$ represents the evanescent waves.

The eigenfunctions $f_{1n}(z)$ in Eq. (1) are given by

$$f_{1n}(z) = N_{1n}^{-1}\ \cos\ k_{1n}(z + h), \quad n = 0, 1, 2, \ldots$$
$$(N_{1n})^2 = \frac{1}{2}\left(1 + \frac{\sin\ 2k_{1n}h}{2k_{1n}h}\right). \tag{3}$$

and also satisfy the following orthogonality.

$$\frac{1}{h}\int_{-h}^{0} f_{1m}(z) f_{1n}(z) dz = \delta_{mn}, \tag{4}$$

where δ_{mn} is the Kronecker delta defined by $\delta_{mn} = 1$ if $m = n$, and $\delta_{mn} = 0$ if $m \ne n$.

In region (II), the radiation potential satisfies the Laplace equation, free surface, and body boundary conditions at upper damping plate $(\partial\phi^{(\mathrm{II})}/\partial z = 1,\ \text{at}\ z = -d_0)$ and side wall of the cylinder $(\partial\phi^{(\mathrm{II})}/\partial r = 0,\ \text{at}\ r = b)$. The velocity potential in regions (II) can be written as the sum of a particular solution and a homogeneous solution.

$$\varphi^{(\mathrm{II})}(r, z) = \psi_P^{(\mathrm{II})}(r, z) + \sum_{n=0}^{\infty} B_n\left(I_0(k_{2n}r) - \frac{I_0'(k_{2n}b)}{K_0'(k_{2n}b)} K_0(k_{2n}r)\right) f_{2n}(z), \tag{5}$$

where I_0 is the modified Bessel function of the first kind. The prime appearing in the superscript denotes the derivative with respect to the argument. The eigenvalues $(k_{20} = -ik_2,\ k_{2n},\ n = 1, 2, \cdots)$ in region (II) are the roots of the dispersion relation $(k_{2n}\ \tan\ k_{2n}d_0 = -\omega^2/g)$, and the normalized vertical eigenfunctions $f_{2n}(z)$ are defined as follows:

$$f_{2n}(z) = N_{2n}^{-1}\ \cos\ k_{2n}(z + d_0), \quad n = 0, 1, 2, \ldots$$
$$(N_{2n})^2 = \frac{1}{2}\left(1 + \frac{\sin\ 2k_{2n}d_0}{2k_{2n}d_0}\right). \tag{6}$$

The eigenfunctions $f_{2n}(z)$ satisfy the orthogonal relation.

$$\frac{1}{d_0}\int_{-d_0}^{0} f_{2m}(z) f_{2n}(z) dz = \delta_{mn}. \tag{7}$$

The particular solutions in region (II) satisfying the inhomogeneous body boundary condition can be written as follows:

$$\psi_P^{(\mathrm{II})}(r, z) = z + \frac{1}{K}, \tag{8}$$