Applied Ocean Research 67 (2017) 1–8

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

On natural modes in moonpools with recesses

Bernard Molin [a,b,*]

[a] Aix Marseille Univ, CNRS, Centrale Marseille, IRPHE, Marseille, France
[b] Bureau Veritas Marine & Offshore SAS, 67/71 Boulevard du Château, 92571 Neuilly sur Seine, France

ARTICLE INFO

Article history:
Received 3 April 2017
Received in revised form 19 May 2017
Accepted 20 May 2017

Keywords:
Drillship
Moonpool resonance
Piston mode
Sloshing mode
Linearized potential flow theory

ABSTRACT

The theoretical model of Molin [6] is extended to the case of rectangular moonpools with one or two recesses, as can be found in some drillships. Obtained natural frequencies and modal shapes of the piston and first sloshing modes are compared with experimental results available in literature, with good agreement. An approximation easy to implement is proposed for the natural frequency of the piston mode. Further illustrative results are presented when some geometrical parameters of the moonpool are being varied.

1. Introduction

Moonpools are vertical openings through the hulls of some marine structures. They usually have vertical walls, from deck to keel. However some moonpools in drillships have “recesses”, some kind of sub-compartments used, for instance, for assembling drilling equipments [9]. As shown in Fig. 1, taken form [5], recesses can be located on the bow side or on the aft side of the moonpool.

Moonpools are prone to bothersome resonance problems, under outer wave action or forward speed, and it is desirable, at the design stage, to be able to predict their resonant frequencies. Natural modes in moonpools consist in the so-called piston mode, up and down motion of the entrapped water, and in sloshing modes, similar to the sloshing modes in a tank.

Molin [6] proposed a theoretical frame to derive the resonant frequencies for rectangular moonpools with vertical walls. His work was based on simplifying assumptions: the floating support is motionless, the waterdepth is infinite, the length and breadth of the support are infinite. The fluid domain is then decomposed into two parts: the moonpool and a semi-infinite fluid domain below the keel level. Linearized potential flow theory is used, the velocity potential being written as an eigen-function expansion in the moonpool. The matching condition with the lower fluid domain is written as an integral equation relating the potential and its vertical derivative. An eigen-value problem is then formulated and solved, yielding the natural frequencies and associated modal shapes of the free surface.

In this paper we follow the same procedure, with the moonpool being decomposed into two parts where different eigen-function expansions are used and need to be matched on the common boundary.

2. Theoretical model

The geometry is illustrated in Fig. 2. The moonpool is supposed to consist in possibly two recesses. We use a rectangular coordinate system *Oxyz* with its origin at the keel line, at one end of the “restriction” part of the moonpool (we use here the coining “restriction” following [1], see also [10], in their study of the MONOBR platform). The restriction and the recesses are rectangular. The length of the restriction is a, its height is d. The length of the left recess is b, the length of the right recess is c, the additional water-height in the upper part is h, so that the total draft is $d+h$. The total length of the moonpool, at the waterline, is $L=a+b+c$, and its width is B (it is the same width for the restriction and for the upper part).

Alike in [6], the waterdepth is assumed to be infinite, and the beam and length of the drillship are taken to the limit when they are also infinite. As a result the fluid domain consists in three parts: a semi-infinite lower subdomain ($-\infty<x<+\infty$; $-\infty<y<+\infty$; $-\infty<z\leq 0$), the restriction ($0\leq x\leq a$; $0\leq y\leq B$; $0\leq z\leq d$), and the upper part of the moonpool ($-b\leq x\leq a+c$; $0\leq y\leq B$; $d\leq z\leq d+h$).

Use is made of linearized potential flow theory. The flow is assumed to periodic in time at a frequency ω: $\Phi(x, y, z, t)=\varphi(x, y, z)\cos(\omega t+\psi)$. In the moonpool the reduced potential φ verifies the

* Correspondence to: Aix Marseille Univ, CNRS, Centrale Marseille, IRPHE, Marseille, France.
E-mail address: bernard.molin@centrale-marseille.fr

http://dx.doi.org/10.1016/j.apor.2017.05.010
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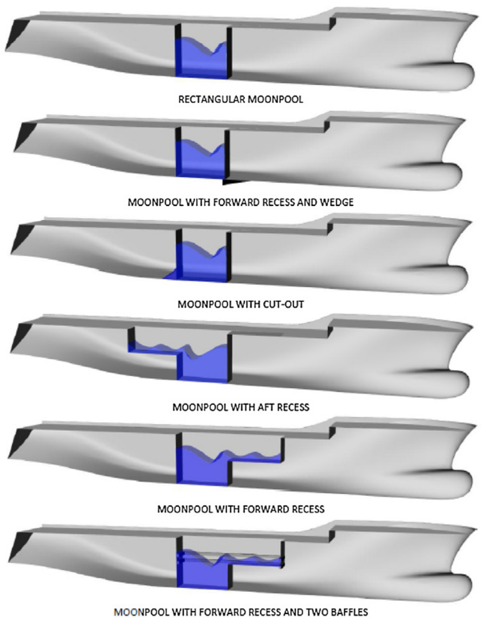

Fig. 1. Types of moonpools on drillships. Taken from [5].

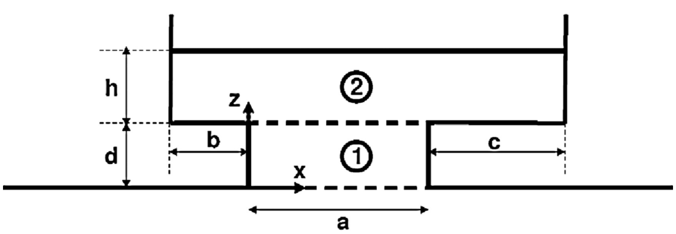

Fig. 2. Geometry.

Laplace equation $\Delta\varphi = 0$, no-flow conditions at the solid boundaries $\varphi_n = \partial\varphi/\partial n = 0$, the free surface condition $g\,\varphi_z - \omega^2\,\varphi = 0$ at $z = d + h$, and a matching condition with the flow in the lower fluid domain, written as [6]:

$$\varphi(x, y, 0) = \frac{1}{2\pi} \int_0^a \mathrm{d}x' \int_0^B \mathrm{d}y' \quad \frac{\varphi_z(x', y', 0)}{\sqrt{(x - x')^2 + (y - y')^2}} \tag{1}$$

Typical moonpool dimensions in drillships are about 40–50 m in length and 10 m in width, and we are here interested in the piston and longitudinal sloshing modes. So we make the simplifying assumption that the moonpool is narrow, so that the flow inside can be idealized as two-dimensional. Note that the flow in the lower fluid domain $z \le 0$ is three-dimensional.

As in [6] we use eigen-function expansions to represent the flow in the moonpool:

$$\varphi_1(x, z) = A_0 + B_0\,\frac{z}{d} + \sum_{n=1}^{\infty} (A_n\,\cosh k_n z + B_n\,\sinh k_n z)\cos k_n x \tag{2}$$

in sub-domain 1 ($0 \le z \le d$), with $k_n = n\pi/a$, and

$$\varphi_2(x, z) = C_0 + D_0\,\frac{z - d}{h} + \sum_{n=1}^{\infty} (C_n\,\cosh\lambda_n(z - d) + D_n\,\sinh\lambda_n(z - d))\cos\lambda_n(x + b) \tag{3}$$

in sub-domain 2 ($d \le z \le d + h$), with $\lambda_n = n\pi/(a + b + c) = n\pi/L$.

The Laplace equation and the no-flow conditions at the end walls are ensured.

The bottom boundary condition writes

$$A_0 + \sum_{m=1}^{\infty} A_m\,\cos k_m x = \frac{1}{2\pi} \int_0^a \int_0^B \frac{B_0/d + \sum_{n=1}^{\infty} B_n k_n\,\cos k_n x'}{\sqrt{(x - x')^2 + (y - y')^2}}\,\mathrm{d}x'\,\mathrm{d}y' \tag{4}$$

Through integrations this can be transformed into the vectorial equation (see [6]):

$$\vec{A} = \mathbf{M_{AB}} \cdot \vec{B} \tag{5}$$

with $\vec{A} = (A_0, \ldots A_n)$, $\vec{B} = (B_0, \ldots B_n)$.

In $z = d$ we match φ_1 and φ_2 and their vertical derivatives. We follow Garrett's method [2]. Consider first the equality of the potentials:

$$A_0 + B_0\,\frac{z}{d} + \sum_{m=1}^{\infty} (A_m\,\cosh k_m d + B_m\,\sinh k_m d)\cos k_m x = C_0 + \sum_{n=1}^{\infty} C_n\,\cos\lambda_n(x + b) \tag{6}$$

which holds for $0 \le x \le a$.

Again we take advantage of the orthogonality of the set $[\cos k_n x]$ over $[0\ a]$. Integrating each side in x over $[0\ a]$, then multiplying with $\cos k_m x$ and integrating again for all m, the following vectorial equation is obtained:

$$\vec{A} + \mathbf{D_B}\ \vec{B} = \mathbf{M_C}\ \vec{C} \tag{7}$$

where $\mathbf{D_B}$ is the diagonal matrix $(1, \tanh k_m d)$, $\mathbf{M_C}$ is a full matrix and $\vec{C} = (C_0, \ldots C_n)$.

Consider now the vertical velocities. They obey the equations

$$\begin{aligned} \varphi_{2z} &= \varphi_{1z} \quad 0 \le x \le a \\ \varphi_{2z} &= \quad 0 \quad -b \le x \le 0 \text{ and } a \le x \le a + c \end{aligned} \tag{8}$$

That is

$$\begin{aligned} &\frac{D_0}{h} + \sum_{m=1}^{\infty} \lambda_m\,D_m\,\cos\lambda_m(\mathrm{x} + \mathrm{b}) \\ &= \frac{B_0}{d} + \sum_{n=1}^{\infty} k_n\,(A_n\,\sinh k_n d + B_n\,\cosh k_n d)\cos k_n x \quad 0 \le x \le a \\ &= 0 \quad -\mathrm{b} \le \mathrm{x} \le 0 \text{ and } \mathrm{a} \le \mathrm{x} \le \mathrm{a} + \mathrm{c} \end{aligned} \tag{9}$$

Now we make use of the orthogonality of the set $[\cos\lambda_m(x + b)]$ over $[-b\ a + c]$. Integrating each side over their domains of validity, then multiplying with $\cos\lambda_m(x + b)$ and integrating again for all m, gives

$$\vec{D} = \mathbf{M_{DA}}\ \vec{A} + \mathbf{M_{DB}}\ \vec{B} \tag{10}$$

with $\vec{D} = (D_0, \ldots D_n)$.

Finally the free surface equation $g\,\varphi_{2z} - \omega^2\,\varphi_2 = 0$ gives

$$\mathbf{D_1}\,\vec{C} + \mathbf{D_2}\,\vec{D} = \omega^2 \quad \left(\vec{C} + \mathbf{D_4}\,\vec{D}\right) \tag{11}$$

with $\vec{D} = (D_0, \ldots D_n)$ and $\mathbf{D_1}$, $\mathbf{D_2}$, $\mathbf{D_4}$ diagonal matrices:

$$\begin{aligned} \mathbf{D_1} &= (0,\ \mathrm{g}\,\lambda_n\,\tanh\lambda_n \mathrm{h}) \\ \mathbf{D_2} &= (\mathrm{g/h},\ \mathrm{g}\,\lambda_n) \\ \mathbf{D_4} &= (1,\ \tanh\lambda_n \mathrm{h}) \end{aligned} \tag{12}$$

From (5) and (7) we get:

$$\vec{B} = (\mathbf{M_{AB}} + \mathbf{D_B})^{-1}\,\mathbf{M_C}\,\vec{C} \tag{13}$$