TẠP CHÍ KHOA HỌC CÔNG NGHỆ HÀNG HẢI ISSN: 1859-316X
JOURNAL OF MARINE SCIENCE AND TECHNOLOGY

RESEARCH ON REDUCING PITCHING MOTION FOR FLOATING STRUCTURES USING ECCENTRIC MASSES

NGHIÊN CỨU GIẢM DAO ĐỘNG XOẮN CHO KẾT CẤU HỆ NỔI SỬ DỤNG THIẾT BỊ GIẢM CHẤN KHỐI LƯỢNG LỆCH TÂM

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Abstract

Floating structures have been applied in many fields such as housing, ports, wind turbines,... Under the action of wave and wind loads, the floating structure will have pitching motion. This can cause danger to the structure or discomfort to the user. Therefore, it is necessary to study suitable devices to reduce pitching motion of floating structures. This paper introduces the application of eccentric mass device to suppress pitching motion of a rectangular box structure. The equations of motion of the floating structure-eccentric mass system are established. The system is assumed to be subject to harmonic excitation. The effectiveness of the device is demonstrated through numerical simulation results. The Pareto front with different masses of the device has also been investigated.

Keywords: *Pitching motion, passive control, floating structures, eccentric masses, optimal design.*

Tóm tắt

Kết cấu nổi được áp dụng trong nhiều lĩnh vực như xây dựng dân dụng, cảng biển, tuabin điện gió,... Dưới tác dụng của các tải trọng sóng và gió, kết cấu nổi sẽ bị dao động xoắn. Điều này có thể gây ra nguy hiểm cho công trình hoặc cảm giác khó chịu cho người sử dụng. Chính vì vậy việc nghiên cứu các thiết bị phù hợp nhằm giảm dao động xoắn của kết cấu nổi là rất cần thiết. Bài báo này giới thiệu việc áp dụng thiết bị khối lượng lệch tâm nhằm giảm dao động xoắn cho kết cấu nổi có dạng hộp chữ nhật. Phương trình chuyển động của hệ kết cấu nổi – khối lượng lệch tâm được thiết lập. Hệ khảo sát được giả thiết chịu kích động điều hòa. Hiệu quả của thiết bị được chứng minh thông qua các kết quả mô phỏng số. Tập Pareto với các khối lượng khác nhau của thiết bị cũng đã được khảo sát.

Từ khóa: *Dao động xoắn, điều khiển bị động, kết cấu hệ nổi, khối lượng lệch tâm, thiết kế tối ưu.*

1. Introduction

In the field of civil engineering, floating structures have been applied to build floating houses (also known as boathouses). In Vietnam, this type of construction has been applied in the Mekong Delta, concentrated in Chau Doc, An Giang [1]. The characteristics of floating houses are that they float completely on the water, move up and down according to the water level and are very suitable for areas affected by floods (Fig. 1). In [2], the authors proposed applying floating house and amphibious urbanization in South-East Asian, contributing to mitigate the damage caused by floods.

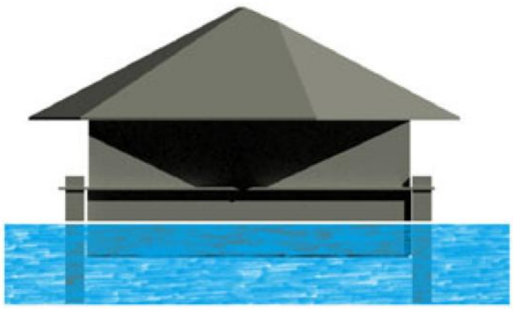

Figure 1. Sketch of a floating house that can move up and down with changes in water level [3]

Floating structures are not only applied to floating houses but also to other types of structures such as floating ports, wind turbines,… As analyzed in [3], floating house structures are only discussed in the field of architecture. In Vietnam, the architecture of floating houses has been mentioned in [4]. However, scientific studies on floating houses are very few when compared to very large floating structures (subject to wave loads) [5-7] or floating wind turbines (subject to both wave and wind loads) [8-10]. This can be explained by the fact that floating houses, especially low-rise houses, are not subject to large loads such as wind and waves, so that they have not received due attention. However, the vibrations of floating houses can cause discomfort to users. Therefore, research on reducing vibrations for floating houses is still very necessary [3].

To reduce torsional vibrations for general structures, the tuned liquid column damper (TLCD) is commonly studied [11-13]. In [14], TLCD is used to reduce the vibrations of floating wind turbines in all directions in the plane. In [3], TLCD is used to reduce pitching motion for floating rectangular box structure, specifically applied to floating houses.

TLCD has proven to be effective in reducing vibrations, however, due to the large size of TLCD and its placement on top the floating structure, it may affect the working space of people as well as the arrangement of equipment. In [15], the eccentric masses are used to reduce vibrations for bridge decks under wind loads. In this paper, the authors propose to use this device placed inside the floating structure to reduce pitching motion.

2. Analysis model and equations of motion

2.1. Analysis model

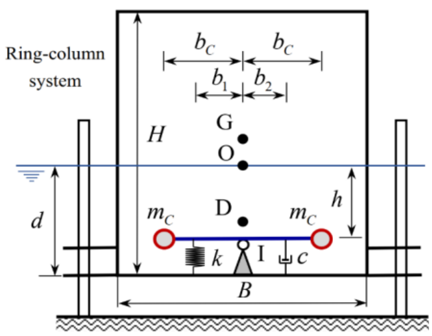

Figure 2. Model of the floating structure-eccentric mass system at static equilibrium position

Consider a floating rectangular box structure with length L, width B, height H and mass m_s [3]. Inside the floating structure, the eccentric masses are arranged as shown in Fig. 2. This device consists of two masses m_C attached to a light rigid bar that can rotate around joint I. The rigid bar is equipped with a spring of stiffness k and a viscous damper of coefficient c, the spring and viscous damper are distances b_1 and b_2 from the rotation joint I, respectively in the horizontal direction. The light bar is a distance h from the water surface. At the equilibrium position, the floating structure is submerged in water a distance d. The center of buoyancy and the center of flotation are denoted by D and O, respectively, while the center of mass of the floating structure is denoted by G.

We have:

$$d = \frac{m_s + 2m_C}{\rho_w BL} \tag{1}$$

where ρ_w is the density of water.

Considering the floating structure using a ring-column system to limit horizontal movement, so we only focus on studying pitching motion [3]. The structure oscillates around point O with a rotation angle θ as shown in Fig. 3. The connecting bar of the eccentric masses has a rotation angle φ. It should be noted that these two rotation angles are chosen as absolute displacements. The center of buoyancy from the initial position D will move to the new position D' and the metacenter is denoted by M.

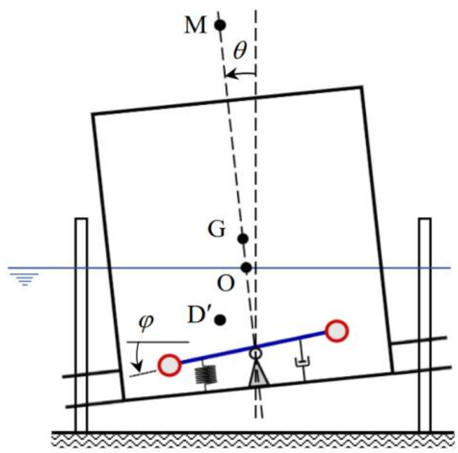

Figure 3. Displacements in the vibration of the system

During vibration of the system, assuming the rotation angles are small, the spring k and the viscous c are equivalent to the torsion spring k_C and the torsion viscous damper c_C. We have:

$$k_C = b_1 k; \quad c_C = b_2 c \tag{2}$$

The optimal parameters will be calculated through k_C and c_C.

2.2. Equations of motion

The kinetic energy of the system includes the ones of the floating structure and the eccentric masses. The kinetic energy of the floating structure is determined:

$$T_s = \frac{1}{2} I_{sO} \dot{\theta}^2 \tag{3}$$

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with I_{sO} being the moment of inertia of the floating structure with respect to the center of flotation O and determined:

$$I_{sO} = I_s + m_s\overline{OG}^2 \tag{4}$$

I_s is the moment of inertia of the floating structure with respect to the center of mass G. Consider the floating structure combined by six plates with three different sizes $B\times L$, $H\times L$ and $B\times H$. The quantity I_s can be determined as follows [3]:

$$\begin{aligned} I_s = &\left[2HLm_s\left(\frac{H^2}{12}+\left(\frac{B}{2}\right)^2\right)+\right.\\ &+2BHm_s\left(\frac{H^2+B^2}{12}\right)+\\ &\left.2BLm_s\left(\frac{B^2}{12}+\left(\frac{H}{2}\right)^2\right)\right]/\\ &\left[2\left(HL+BH+BL\right)\right] \end{aligned} \tag{5}$$

The velocity of the mass m_C on the left:

$$v_1^2 = h^2\dot{\theta}^2 + b_C^2\dot{\varphi}^2 + 2hb_C\sin\left(\varphi-\theta\right)\dot{\theta}\dot{\varphi} \tag{6}$$

The velocity of the mass m_C on the right:

$$v_2^2 = h^2\dot{\theta}^2 + b_C^2\dot{\varphi}^2 - 2hb_C\sin\left(\varphi-\theta\right)\dot{\theta}\dot{\varphi} \tag{7}$$

The kinetic energy of the eccentric masses:

$$T_C = \frac{1}{2}m_C v_1^2 + \frac{1}{2}m_C v_2^2 \tag{8}$$

The kinetic energy of the system:

$$T = \frac{1}{2}I_{sO}\dot{\theta}^2 + m_C h^2\dot{\theta}^2 + m_C b_C^2\dot{\varphi}^2 \tag{9}$$

The potential energy of the system includes the gravitational potential energies of the floating structure and the eccentric masses, the elastic potential energy of the torsion spring and the hydrostatic energy. The reference datum is chosen at the water surface.

The potential energy of the floating structure:

$$\Pi_s = m_s g\overline{OG}\cos\theta \tag{10}$$

The potential energy of the mass m_C on the left:

$$\Pi_1 = -m_C g\left(h\cos\theta + b_C\sin\varphi\right) \tag{11}$$

The potential energy of the mass m_C on the right:

$$\Pi_2 = m_C g\left(-h\cos\theta + b_C\sin\varphi\right) \tag{12}$$

The potential energy of the torsion spring k_C:

$$\Pi_C = \frac{1}{2}k_C\left(\varphi-\theta\right)^2 \tag{13}$$

The hydrostatic energy of the submerged part of floating structure in case of small vibrations [3, 16]:

$$\begin{aligned} &\Pi_{Hydrostatic} = \\ &\left(m_s+2m_C\right)g\left(\frac{B^2\sin^2\theta}{24d\cos\theta}+\frac{d\cos\theta}{2}\right) \end{aligned} \tag{14}$$

The potential energy of the system:

$$\begin{aligned} \Pi = &\; m_s g\overline{OG}\cos\theta - 2m_C gh\cos\theta \\ &+\frac{1}{2}k_C\left(\varphi-\theta\right)^2 + \\ &\left(m_s+2m_C\right)g\left(\frac{B^2\sin^2\theta}{24d\cos\theta}+\frac{d\cos\theta}{2}\right) \end{aligned} \tag{15}$$

The corresponding dissipation function of the viscous damper c_C is determined:

$$\Phi = \frac{1}{2}c_C\left(\dot{\varphi}-\dot{\theta}\right)^2 \tag{16}$$

The nonconservative forces:

$$Q_\theta = M\left(t\right);\; Q_\varphi = 0 \tag{17}$$

where M is the moment due to external forces acting on the floating structure.

Substituting (4)-(17) into the Lagrange equation system and pay attention to small vibrations ($\sin\theta\approx\theta$, $\cos\theta\approx 1$), we have the system of motion equations:

$$\begin{aligned} &\begin{bmatrix} I_{sO}+2m_C h^2 & 0 \\ 0 & 2m_C b_C^2 \end{bmatrix}\begin{Bmatrix}\ddot{\theta}\\ \ddot{\varphi}\end{Bmatrix} \\ &+\begin{bmatrix} c_C & -c_C \\ -c_C & c_C \end{bmatrix}\begin{Bmatrix}\dot{\theta}\\ \dot{\varphi}\end{Bmatrix} \\ &+\begin{bmatrix} \left(m_s+2m_C\right)g\overline{OM}+k_C-m_s g\overline{OG}+2m_C gh & -k_C \\ -k_C & k_C \end{bmatrix} \\ &\begin{Bmatrix}\theta\\ \varphi\end{Bmatrix} = \begin{Bmatrix}M\\ 0\end{Bmatrix} \end{aligned} \tag{18}$$

in which [3]:

$$\overline{OM} = B^2/\left(12d\right) - d/2 \tag{19}$$

where $\overline{OM}$ is the distance from the center of flotation O to the metacenter M.

Introduce new variables:

$$k_s = m_s g\left(\overline{OM} - \overline{OG}\right);\ \bar{h} = h + \overline{OM} \quad (20)$$

Equation (18) then has the form:

$$\begin{bmatrix} I_{sO} + 2m_C h^2 & 0 \\ 0 & 2m_C b_C^2 \end{bmatrix}\begin{Bmatrix} \ddot{\theta} \\ \ddot{\varphi} \end{Bmatrix} + \begin{bmatrix} c_C & -c_C \\ -c_C & c_C \end{bmatrix}\begin{Bmatrix} \dot{\theta} \\ \dot{\varphi} \end{Bmatrix} + \begin{bmatrix} k_s + 2m_C g\bar{h} + k_C & -k_C \\ -k_C & k_C \end{bmatrix}\begin{Bmatrix} \theta \\ \varphi \end{Bmatrix} = \begin{Bmatrix} M \\ 0 \end{Bmatrix} \quad (21)$$

It should be noted that [3]:

$$\omega_s = \sqrt{k_s / I_{sO}} \quad (22)$$

where ω_s is the pitching vibration frequency of the floating structure.

3. Design optimization

Assume that the moment has a harmonic form [3]:

$$M = M_0 e^{i\Omega t} \quad (23)$$

Then the displacements of the system have the form:

$$\theta = \theta_0 e^{i\Omega t};\quad \varphi = \varphi_0 e^{i\Omega t} \quad (24)$$

Substituting (23), (24) into (21), we will find the amplitudes θ_0 and φ_0.

The absolute value of θ_0 has the form:

$$\left|\theta_0\right| = \sqrt{\frac{\left(\frac{M_0}{I}\right)^2\left[\left(\gamma^2 - \Omega^2\right)^2 + 4\delta^2\Omega^2\right]}{\Delta}} \quad (25)$$

in which:

$$\Delta = \left[\left(\gamma_0^2 - \Omega^2\right)\left(\gamma^2 - \Omega^2\right) - 4\delta_0\delta\,\Omega^2 + \frac{2\delta c_C\Omega^2 - \gamma^2 k_C}{I}\right]^2 + \left[2\left(\gamma_0^2 - \Omega^2\right)\delta\,\Omega + 2\left(\gamma^2 - \Omega^2\right)\delta_0\,\Omega - \frac{k_C c_C \Omega}{I\, m_C b_C^2}\right]^2 \quad (26)$$

$$2\delta_0 = \frac{c_C}{I_{sO} + 2m_C h^2};\quad \gamma_0^2 = \frac{\left(k_s + k_C + 2m_C g\bar{h}\right)}{I_{sO} + 2m_C h^2};\quad I = I_{sO} + 2m_C h^2;\quad 2\delta = \frac{c_C}{2m_C b_C^2};\quad \gamma^2 = \frac{k_C}{2m_C b_C^2} \quad (27)$$

The dynamic magnification factor is evaluated through the quantity [3, 17]:

$$DMF = \left|\theta_0\right| / \left(M_0 / k_s\right) \quad (28)$$

Set frequency ratio:

$$\beta = \Omega / \omega_s \quad (29)$$

Consider the frequency of the moment varying in the range:

$$\Omega \in \left[\beta_1\omega_s;\ \beta_2\omega_s\right] \quad (30)$$

In the above frequency range, the DMF quantity has a maximum value DMF_{max}. Then the optimization problem becomes finding the values of k_C and c_C that satisfy the objective function [18, 19]:

$$\left(DMF_{\max}\right)\Big|_{\beta_1}^{\beta_2} \to \min \quad (31)$$

4. Example

Considering a floating rectangular box structure with parameters as shown in Table 1 [3].

Table 1. The parameters of the floating structure

Symbol	Value	Unit
B	2.31	m
H	2.59	m
L	5.95	m
m_s	2150	kg
I_s	3936.8	kg/m^2
ρ_w	1000	kg/m^3
M_0	100	Nm

Choose $\beta_1 = 0.5$; $\beta_2 = 1.5$. Arrange the connecting bar of eccentric masses at a position 30 cm from the bottom of the floating structure. Thus, we have $h = d - 0.3$ (m). The distance b_C is chosen to be 1 m.

Set the mass ratio:

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$$\mu = 2m_C / m_s \qquad (32)$$

Take $\mu = 0.07$ [3], we find the values of k_C and c_C that satisfy the objective function (31). Using Matlab software, we have the optimal values k_{Copt} = 735.38N/m, c_{Copt} = 58.81Ns/m. The corresponding dynamic response of the floating structure is DMF_{max}=8.47. The graph of the variation of DMF_{max} according to the frequency ratio with the values of k_{Copt} and c_{Copt} is shown in Fig. 4.

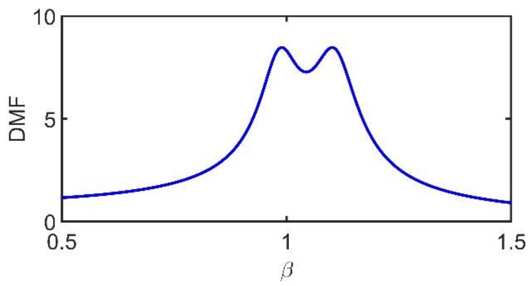

Figure 4. Dynamic response of the structure according to frequency ratio (μ = 0.07)

Thus, the efficiency of the eccentric masses is equivalent to that of the TLCD in [3] with DMF_{max}=8.405. However, as analyzed above, because the TLCD device is arranged on top of the floating structure, it will affect the operating space. Meanwhile, the eccentric masses are arranged at the bottom of the floating structure, so this problem will be overcome.

5. Pareto front

In this section, the Pareto front will be established, the optimal DMF_{max} values will be investigated with different mass ratios μ. The values of μ are considered in the range [0.01 ÷ 0.15]. The graph of the variation of the optimal DMF_{max} with μ is shown in Fig. 5.

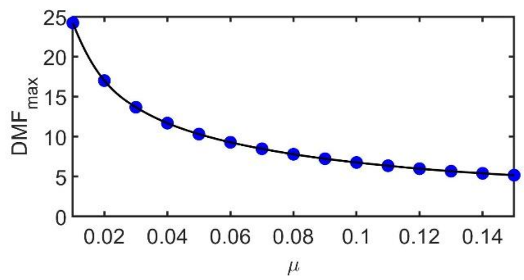

Figure 5. Variation of optimal DMF_{max} with respect to μ

As seen in Fig. 5, the optimal DMF_{max} values varies in the range of 5.17 ÷ 24.22 with the mass ratio varying in the range of 1% ÷ 15%. Based on this Pareto front, design engineers can choose the mass of the damping device used appropriately.

6. Conclusion

The paper has proposed the solution to reduce pitching motion for floating structures. The device used is eccentric masses arranged on the bottom of the floating structure. Some of the main contents presented in the paper:

- Establishing the vibration equations of the floating structure-eccentric mass system using the Lagrange method.
- The parameters of the damping device are optimized so that the vibration reduction efficiency is maximum.
- The calculation example is referenced from the reputable article. The numerical simulation results show the effectiveness of the proposed device.
- The Pareto front has been investigated to evaluate the optimal vibration reduction efficiency with different masses of the damping device.
- The calculation results in the paper can be applied to reduce pitching motion for floating structures in general and floating houses in particular.

The next research direction of the paper is to apply the proposed device to reduce vibrations for very large floating structures or wind turbines that subject to wave and wind forces.

Acknowledgements

This research is funded by Vietnam Maritime University under grant number: **DT24-25.86**.

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Received: 21/01/2025
Revised: 21/02/2025
Accepted: 22/02/2025