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Experimental Study of Wave Resonance in a Narrow Gap with Various Edge Shapes

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Abstract

The effect of edge shapes on the piston mode response in a narrow gap formed between two identical fixed floating boxes is investigated by means of wave flume tests. The experimental results confirmed that the edge shape has significant effects on the resonant wave height and resonant frequency. The maximum response amplitude and the resonance frequency increase with the increase of the roundness of gap entrance corners. The maximum resonant wave height for the curved entrance corner cases is more than 7 times higher than the incident wave height while it is about 5 times for the sharp-corner case. Energy dissipation is thought to be the cause for the observed edge shape effects.

Introduction

Violent resonant oscillation of water column in narrow gaps formed by floating vessels may occur as the incident wave frequency is close to the natural frequency of water mass trapped in the gap, which is often referred to as the gap resonance problem. Such resonance responses of water mass in the gap can cause undesirable motions of the vessels, thus affecting normal operations of the vessel such as side-by-side offloading operations between Liquefied Natural Gas (LNG) carries and Floating Liquefied Natural Gas (FLNG) platforms.

Hydrodynamic characteristics associated with the gap resonance have attracted extensive attentions in the past decades. Within linear potential flow theory, the quasi-analytical approaches [1-2] were used to estimate the resonant frequency. Analogue to fluid oscillations in a U-tube, a theoretical formula [3] was also proposed to estimate the natural frequency of fluid in the narrow gap between twin boxes with sharp edges. A series of laboratory tests [3] were also performed to study the resonance characteristics.

Although conventional potential flow models are able to provide reasonable predictions of the resonant frequency, they often over-predicts the resonant wave amplitude significantly. To overcome this problem, various artificial damping [4-10] is introduced in potential flow models with reasonable success. However no systematic approach has been established to determine the artificial coefficient in those modified potential flow models. To explain the discrepancy between the conventional potential solutions and experimental observations, the nonlinearity of free surface was examined [11-13]. Furthermore, numerical simulations within viscous flow theory [7-8, 14-15] were also conducted to understand the dissipative effects. Indeed, it was confirmed that the flow separation and vortex shedding from the sharp corners of the floating structures play an important role in the resonant response. Numerical simulations based on viscous flow model showed that the gap entrance configuration has significant effects on both the resonant frequency and wave height [14].

This work studied the effects of edge configurations on the gap resonance by laboratory tests. Special attentions were paid on the damping/dissipative effects. The dependence of the resonant frequency on the edge radius was examined. In addition, energy dissipation rate is quantified through measured reflection and transmission coefficients.

Experiments

Laboratory tests were carried out in a wave flume with 56m in length, 0.7m in width and 0.7m in depth. An overview of the experimental set-up is shown in Figure 1. Two identical boxes with draft D = 0.25m, gap spacing B_g = 0.05m and breadth B = 0.5m were fixed in the wave flume. The model boxes were made of plexiglass plates of 1cm thickness. Six wave gauges were used to measure the wave elevations. As shown in Figure 1, the wave gauge G_4 was located at the center of the narrow gap, while G_3 and G_5 were arranged 5cm in front of the leading Box A and 5cm behind the rear Box B, respectively. In order to separate the incident waves and the reflected waves, the wave gauges G_1 and G_2 were mounted at 1m and 1m+L/4 in front of the Box A, respectively, where L denotes the incident wavelength. The acquisition rate of the wave gauges is 100Hz, and the absolute error was confirmed to be less than ±1.5mm based on calibration tests.

Various edge shapes of the twin boxes were considered in the laboratory tests, including one sharp-corner shape and four round-corner shapes. The edge configuration was measured by using a non-dimensional parameter of the roundness, namely R/B, where R is the radius of the round corner. The sharp-corner case corresponds to R/B = 0 while for the other round-corner cases the roundness are R/B = 0.05, 0.10, 0.20 and 0.30 respectively.

A series of regular waves with periods ranging from 0.90s to 1.50s were generated in the wave flume with a constant water depth h = 0.5m. For each test, about 30 incident waves were generated to capture fully developed responses. The incident wave height H_i was fixed 2.4cm for all tests. The estimated wave steepness H_i/L was generally less than 0.02, suggesting the incident waves were in the linear range.

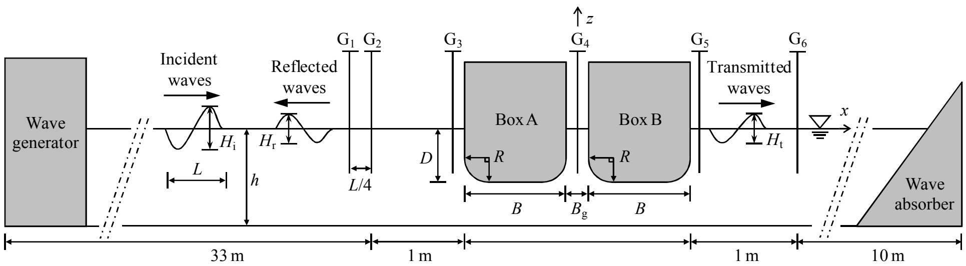

Figure 1. Overview of experimental set-up with constant parameters of $D = 0.252$m, $B = 0.5$m, $B_g = 0.05$m,$h = 0.5$m and $H_i = 0.024$m.

Theoretical analysis

Energy dissipation ratio in the response was quantified in terms of reflection coefficients and transmission coefficients in this work. A sketch of the gap resonance problem is illustrated in Figure 2, including fixed floating twin boxes with round edges separated by a narrow gap.

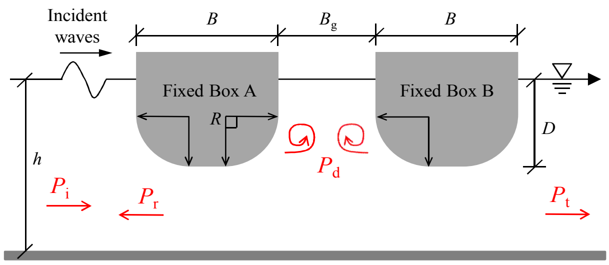

Figure 2. Sketch of gap resonance between two identical fixed floating boxes with round edges.

Considering the law of energy conservation, the incident wave energy flux P_i should be equal to the summation of those from reflection waves, transmission waves and dissipative effects, which can be represented by

$$P_i = P_r + P_t + P_d \tag{1}$$

where P_r, P_t and P_d denote the reflected, transmitted and dissipated energy fluxes, respectively. The three wave energy fluxes in equation (1) can be uniformly expressed as follows,

$$P_{i,\,r,\,t} = \frac{\rho g \omega}{16k}\left(1 + \frac{2kh}{\mathrm{sh}(2kh)}\right) H_{i,\,r,\,t}^2 \tag{2}$$

where k is the wave number, g the gravitational acceleration and ω theangular frequency of the incident waves; $H_{i,\,r,\,t}$ represents the wave heights associated with the incident, reflection and transmission waves, respectively, which can be obtained by experimental measurements. Note that the possible high-order wave modes involved in the resonant response are neglected here. Thus, the dissipative energy flux P_d can be calculated by

$$P_d = \frac{\rho g \omega}{16k}\left(1 + \frac{2kh}{\mathrm{sh}(2kh)}\right)\left(H_i^2 - H_r^2 - H_t^2\right) \tag{3}$$

Further considering the definitions of reflection coefficient and transmission coefficients, namely, $K_r = H_r/H_i$ and $K_t = H_t/H_i$, the energy dissipation ratio K_d can be obtained by

$$K_d = \frac{P_d}{P_i} = 1 - K_r^2 - K_t^2 \tag{4}$$

Equation (4) is used in this work to evaluate the energy dissipation ratio.

Results and Discussion

Time Series

Figure 3 shows a typical example of time records of the free surface elevations at the wave gauge G_4. It can be seen that water oscillations in the gap are nearly simple harmonic at equilibrium. Figure 3(*a*) and 3(*b*) correspond to a resonant frequency and the non-resonant frequency, respectively. It can be seen that the wave height at the resonant frequency is obviously higher than that at the non-resonant frequency. It was found that the wave periods required to reach equilibrium states in the tests depend on the frequency of incoming waves. For example, it generally needs more periods for the oscillation to reach equilibrium at small frequencies.

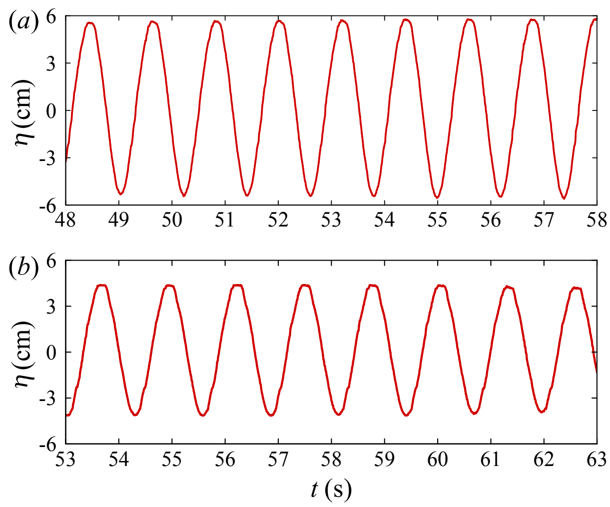

Figure 3. Time series of the free surface elevations in the gap under various non-dimensional incident wave frequencies $\omega/(g/B)^{0.5}$ for $D = 0.25$m, $B = 0.5$m, $B_g = 0.05$m, $R/B = 0$, $h = 0.5$m and $H_i = 0.024$m. (a) $\omega/(g/B)^{0.5} = 1.192$ (Resonant condition); (b) $\omega/(g/B)^{0.5} = 1.108$ (Non-resonant condition)

Resonant Response

To demonstrate the influence of edge configurations on the responses of fluid oscillation in the gap, the variations of relative wave height H_g/H_i with incident wave frequency under various edge configurations are compared in Figure 4. It can be seen that as the edge configuration changes from the sharp corner ($R/B = 0$) to the round corner with small roundness of $R/B = 0.05$, the resonant wave height (maximum H_g/H_i) in the narrow gap increases dramatically from 4.90 to 7.93. The previous numerical simulations by using viscous flow model [15] have shown strong flow separations and vortex shedding around the entrances of the narrow gaps formed by multiple rectangular boxes with sharp edges. As a contrast, the viscous numerical simulations [14] conducted for twin boxes with round edges suggested that the vortical motion is relatively weak. Therefore, it suggests that the substantial increase in the resonant wave amplitude can be mainly attributed to the decrease of resistance forces since the vortical motion weakens as the sharp corner changes to round corners.

In addition, the comparison between R/B = 0 and 0.05 in Figure 4 suggests that the resonant frequency changes little. An explanation is that the small change of the edge shapes hardly leads to remarkable alterations of the fluid mass that involves in the oscillation.

As the roundness R/B increases further from 0.05 to 0.20, the resonant wave height shows a general trend of decrease. At the largest roundness of R/B = 0.30, the resonant wave height drops to 7.23, which is the smallest value for the round-corner cases in this work. The resonant frequency $\omega_R/(g/B)^{0.5}$ is found to increase from 1.19 at R/B = 0.05 to 1.35 at R/B = 0.30.

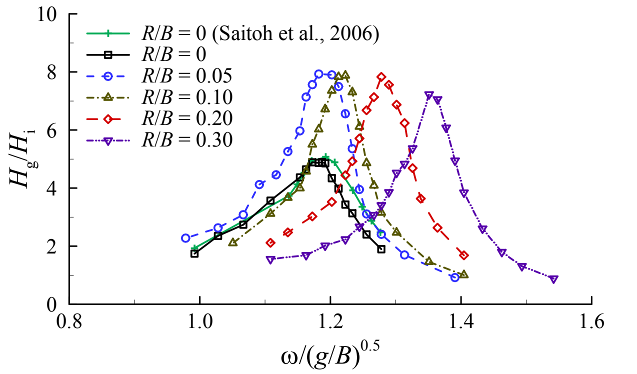

Figure 4. Variations of wave height H_g/H_i in narrow gap with incident wave frequency at various R/B. (D = 0.252m, B = 0.5m, B_g = 0.05m, h = 0.5m and H_i = 0.024m)

Resonant Frequency

The dependence of the resonant frequency on the roundness is examined in Figure 5. The linear potential solutions calculated by using the boundary element model developed in [7-8] are compared with the experimental data. The comparison shows excellent agreement between the numerical solutions and experimental measurements. The good agreement between the linear potential solutions and experimental data implies that the influence of damping on the resonant frequency is rather small. Ignoring damping does not give rise to noticeable influence on the predictions of the resonant frequency.

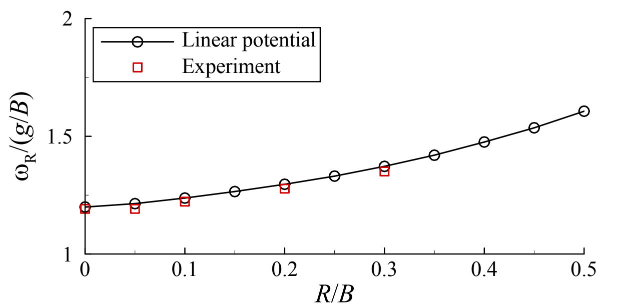

Figure 5. Dependence of resonant frequency $\omega_R/(g/B)^{0.5}$ on edge roundness R/B. (D = 0.252m, B = 0.5m, B_g = 0.05m,h = 0.5m and H_i = 0.024m)

In addition, it can be seen that the resonant frequency increases with the roundness in an approximate exponential function. As mentioned before, we hold that the increase of the edge roundness leads to the decrease of the fluid mass that involves the oscillation, which leads to the resonant frequency shifting to higher values.

Reflection and Transmission Coefficients

The energy relationships under various frequencies at the fixed incoming wave amplitude are illustrated in Figure 6, including the cases of sharp edges and round edges, respectively. First of all, we should state that for the results of measured coefficients in Figure 6 which are outside the range of 0 - 1, they are unphysical. We believe this is caused by the uncertainties in the measurements. Around the

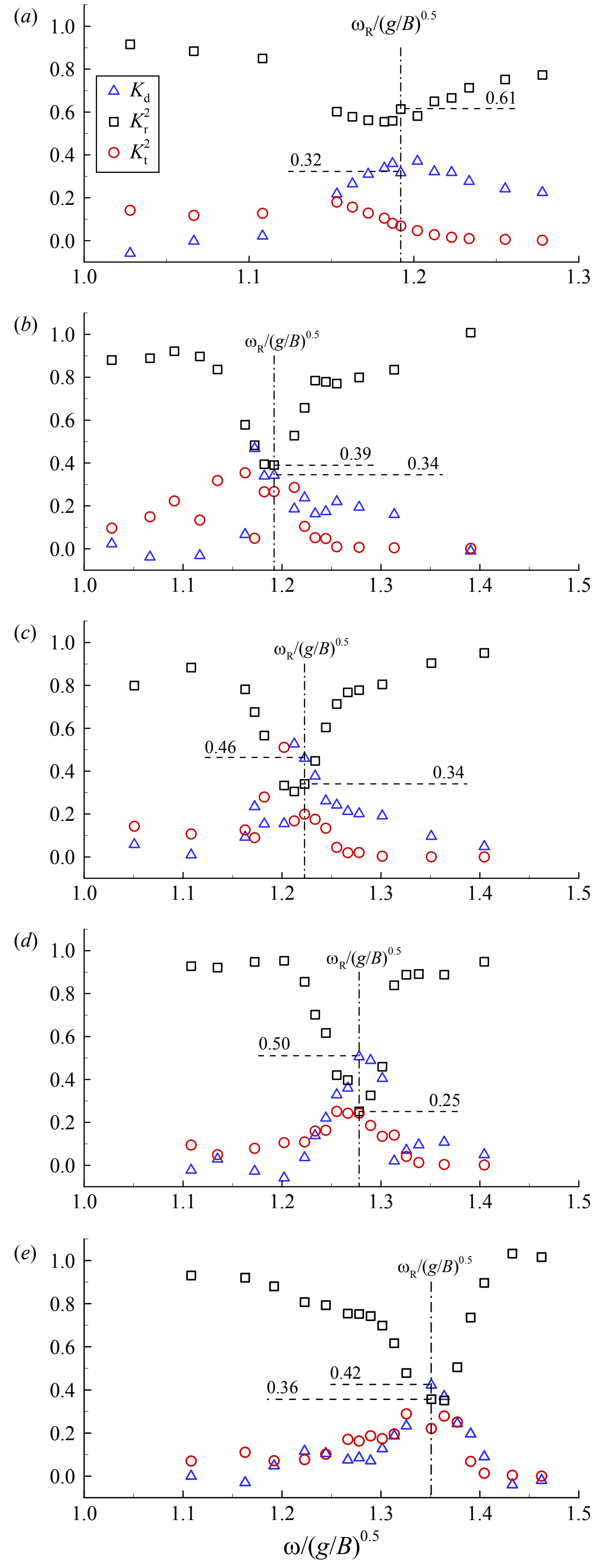

Figure 6. Experimental results of squared reflection coefficient K_r^2, squared transmission coefficient K_t^2 and dissipation coefficient K_d for twin boxes with various round edges: (a) R/B = 0; (a) R/B = 0.05; (c) R/B = 0.10; (d) R/B = 0.20; (e) R/B = 0.30. (D = 0.252m, B = 0.5m, B_g = 0.05m, h = 0.5m and H_i = 0.024m)

resonant frequencies, the reflection coefficient K_r approaches to the minimum while the dissipation ratio coefficient K_d approaches to the maximum. Considering the experimental accuracy and errors, the observed peaks of the reflection and dissipation coefficients are regarded at the exact resonant frequency in the discussion. In Figure 6(*a*), it can be seen that the reflection coefficient approaches to the minimum with K_r^2 = 0.61 at resonance. Besides the dissipation parameter K_d is observed to attain the maximum with K_d = 0.32, which suggests nearly 32% of incoming wave energy is dissipated. This indicates that the most significant energy dissipation takes place at resonance. Moreover, it is interesting to find that the maximum transmission coefficient appears at 1.153, somewhat slightly smaller than the resonant frequency.

As presented in Figures 6(*b*)-6(*e*), generally speaking, the variation trends of the three coefficients are similar to the observations for the sharp corner case. The minimum reflection coefficients and maximum of dissipation coefficients appear around the resonant frequencies. Special attention is paid to the peaks of the dissipation coefficient. It can be seen that the maximum dissipation coefficients at the resonant frequencies for various round corners are roughly within 0.34 - 0.50, which are larger than that observed for the sharp edge case, which is K_d = 0.32 as seen in Figure 6(*a*). It suggests that a higher percentage energy dissipation is involved in the round corner cases. The larger dissipation coefficients with round corner cases are attributed to the substantial increase of the velocity in the narrow gap and around the gap entrance since much larger amplitudes of fluid oscillations are observed for the round corner cases. Indeed, vortical fluid motion around the gap entrance becomes weak for round edges, which has been illustrated in the viscous flow simulations by Moradi *et al*. (2015).

As for the special case of R/B = 0.05, the resonant/natural frequency is observed roughly equal to the sharp-edge case. Therefore the absolute incident wave energy flux at resonance is basically identical for two cases of R/B = 0 and R/B = 0.05 in terms of equation (3). Comparing Figure 6(*a*) with Figure 6(*b*), the slightly larger dissipation ratio at resonance observed for the latter case corresponds to more dissipation. An explanation is that for the sharp-edge case, although the damping force is expected to be larger due to the sharp-edge effect, the mean local flow velocity is relatively lower. The substantial increase in resonant wave height H_g/H_i as the roundness changes from R/B = 0 to R/B = 0.05 confirms the growth in mean local flow velocity. In addition, it can be found that the reflection coefficient decreases from K_r^2 = 0.61 to K_r^2 = 0.39 as the roundness increases to R/B = 0.05, while the transmission waves increase significantly.

Conclusions

This study investigated the effects of the edge shapes on the fluid resonance in the narrow gap between two identical fixed floating boxes by laboratory tests. It was found that the edge shapes have significant influence on the resonant wave height. The maximum resonant wave height for the round-edge cases was experimentally observed to be more than 7 times higher than the incident wave height. The resonant frequency was observed to increase with the radius of round edges. Energy dissipation under the resonant condition was found to increase as the edge shape changes from sharp to round shapes.

Acknowledgments

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