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Two dimension numerical study of resonant free surface motion in the gap between two fixed vessels

Hongchao Wang[1], Scott Draper[2], Wenhua Zhao[1], Hugh Wolgamot[1] and Liang Cheng[2]

[1] Centre for Offshore Foundation Systems
University of Western Australia, Western Australia 6009, Australia

[2]School of Civil, Environmental and Mining Engineering
University of Western Australia, Western Australia 6009, Australia

Abstract

The study focuses on wave induced oscillations of flow inside a narrow gap formed by two identical boxes arranged side-by-side. The problem to be analysed is that of gap resonance behaviours with different gap entrance shapes, incident wave steepness and model scales. We employ the open-source CFD package OpenFOAM and restrict the problem to two-dimensional geometry and fixed boxes. It is found that as wave steepness increases, the frequency corresponding to the maximum response of the fluid in the gap will shift to higher frequency and the response curve closely resembles that of a Duffing oscillator with a hardening spring (as also reported by Vinje, 1991), depending on different entrance shapes. The results also show that a pronounced scaling effect is more evident for cases with rounded corners compared with counterparts with square corners or bilge keels. This may have implications for drawing conclusions applicable to full scale from wave tank tests.

Introduction

Offloading of LNG from a floating facility to a tanker may be performed in either side-by-side or stern-to-bow configurations. Currently the former is favoured, though the closeness of the two vessels leads to a long and relatively narrow gap where there is the potential for large amplifications of incident wave motion. Due to the resonant behaviour at certain incident wave frequencies (referred to as "resonant frequencies"), this amplification may have a significant impact on offloading operations. The resonant water motions which are referred to as gap resonance take place in the natural modes of the gap: (a) the sloshing modes where water moves back and forth in-between the vertical walls and (b) the piston mode where water inside the gap heaves up and down somewhat like a rigid body. For narrow gaps the sloshing modes occur at such high frequency that they are of less practical relevance. In 3D a series of modes with different numbers of half wavelengths along the gap are present, but these do not occur in 2D.

Early numerical investigations of gap resonance problems were mainly based on potential flow model. Although potential flow is a powerful method in general, for narrow gaps it tends to over-predict resonant amplitude [4,8]. Two mechanisms may be responsible for the discrepancy, i.e., nonlinear free surface and viscous effects. In order to resolve the problem of over-prediction near resonant regions, many researchers choose to utilize "lid method" or "artificial damping" to suppress the unrealistic wave elevations [1,2,6]. These methods, however, do not capture the physical essence of the problem. As a result, a fully nonlinear viscous model is needed to enable examination of the flow field to provide physical explanations. Lu et al. [5] investigated a 2D gap resonance problem using CFD methods. The results agree well with experimental data, indicating viscous flow model is capable of predicting such problems with accuracy. Moradi et al. [7] also carried out a 2D numerical study using viscous flow model to examine the influence of extensive parameters, i.e., gap width, entrance shape, body draft and breadth on surface elevations in a narrow gap. To the best of the author's knowledge, nonlinear and scaling effects of gap resonance problem have not been studied using a fully nonlinear viscous model. Therefore, the purpose of the present paper is to investigate the gap resonance problem with regard to nonlinear and scaling effects with different entrance shapes. The model to be analysed is a simple two-dimensional system consisting of two fixed boxes, representative of vessels in a side-by-side offloading arrangement.

Numerical Methods

Numerical Wave Flume Setup

A fully nonlinear viscous numerical wave flume was established using waves2Foam [3]. The definition sketch of computational domain is shown in Figure 1. Two identical boxes are arranged side-by-side with incoming waves propagating from left to right. The body width B, draft D, gap width B_g and water depth h at lab scale are chosen as (0.5, 0.252, 0.05, 0.5) m to render the numerical results comparable with those obtained in the experiments of [9]. Relaxation zones are implemented at both ends of the flume to facilitate wave generation and avoid wave reflections from the boxes and outlet boundary.

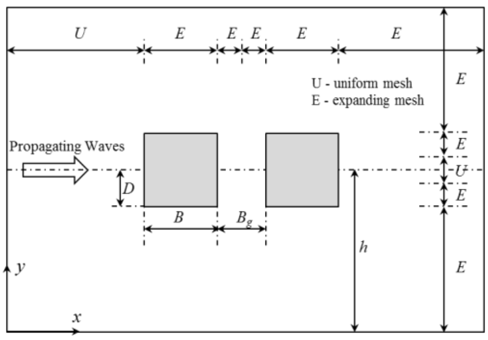


Figure 1. Definition sketch of computational domain.

Mesh independence study

A mesh independence study was performed to ensure solution validity and optimal computation time. For water wave generation, a standard rule of thumb is to choose mesh resolution based on wave length and wave height. In this paper, 10 cells per wave height and 80 cells per wave length are adopted for wave generation. Based on the size of nearest cell to the wall, three different meshes inclusive of fine, medium and coarse meshes were used in order to determine the suitable mesh for resolving the boundary layers. The mesh parameters and corresponding time series of free surface elevations in the middle of the gap at resonance are shown in Table 1 and Figure 2, respectively. The results of the medium mesh agree well with that of the fine mesh. Therefore, the medium mesh is set as a benchmark standard in the following study. The numerical results (not shown here) have been successfully validated against experimental data using the medium mesh and thus demonstrating the present numerical wave flume is capable of predicting the resonant behaviours in the gap.

	Coarse	Medium	Fine
Wall distance [m]	2.1e-3	4.1e-4	2.1e-4
Number of cells	98388	154092	184428

Table 1. Mesh details with different resolutions.

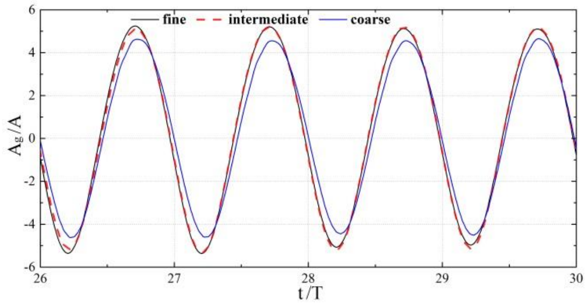


Figure 2. Time series of free surface elevation in the gap with different mesh resolutions.

Results and Discussion

Entrance Shape Effect

In this section three different entrance shapes are examined as sketched in Figure 3. The entrance width of the rounded entrance shape in Figure 3(c) is $B_g + 2r$, where r is the radius of rounded corner with radius to gap width ratio r/B_g equal to 1. The apexes of the bilge keels in Figure 3(b) are coincident with the corresponding vertices of the square corner counterpart in Figure 3(a) so that the widths of both entrances are the same. The base of each bilge keel is mounted in the middle of the corresponding corner.

Response amplitude curves of free surface elevation in the gap A_g, normalised by the incident wave amplitude A, deduced from regular wave tests (once a steady-state had been reached) for the different entrance shapes are plotted in Figure 4. The scale is 'lab' scale so the water depth h is 0.5 m, and the incident wave amplitude is 0.012 m. It can be seen that resonances occur at the same frequency for the bilge keel and square corner entrance while resonance for the rounded entrance occurs at a higher frequency. This is due to the fact that the entrance widths of both setups are the same and there is little change in the confined volume of fluid in the gap when the entrance shape is altered from square corners to protruded bilge keels. Additionally, the shift of resonant frequency to higher frequency for rounded entrance is consistent with the results as reported in [7].

Concerning the entrance effect on the free surface resonant amplitude, it is useful to note that this problem is analogous to fluid flowing from a reservoir into a pipe (or vice versa). In this analogous scenario the pipe entrance shape is well-known to have a significant effect on the pressure and flow within the pipe in accordance with standard hydraulic entrance and exit loss coefficients. Specifically, the analogue would suggest minimal losses are expected for the rounded corners and maximum losses are expected for the bilge keels. These expectations are consistent with the results in Figure 4, which show that the rounded corner entrance has the largest wave amplification at resonance, presumably due to little energy loss near the entrance, while the bilge keel has the smallest resonant amplitude, presumably due to larger energy dissipation near the entrance. Specifically, the maximum elevations in the gap of the three entrance configurations are 10.90, 5.16 and 3.94, respectively.

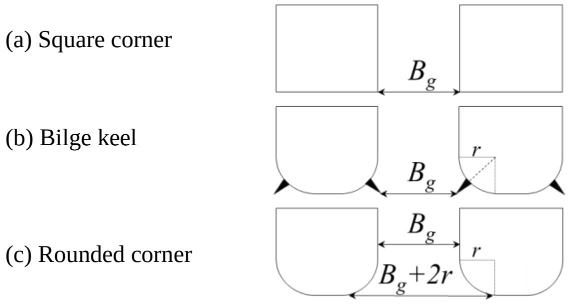


Figure 3. Sketch of entrance shape.

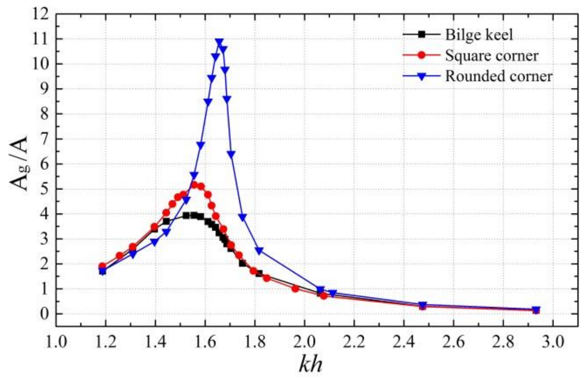


Figure 4. Amplitude response curves of free surface elevation in the gap with different entrance shapes (A = 0.012 m, lab scale).

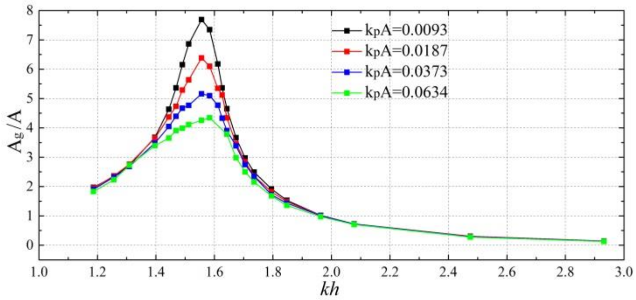
Nonlinear Effects

Test condition	Square	Bilge keel	Rounded
A= 0.003 m	kh = 1.56	kh = 1.58	kh = 1.64
A= 0.006 m	kh = 1.56	kh = 1.56	kh = 1.64
A= 0.012 m	kh = 1.56	kh = 1.56	kh = 1.66
A= 0.020 m	kh = 1.58	kh = 1.56	kh = 1.69
A= 0.025 m	/	/	kh = 1.70

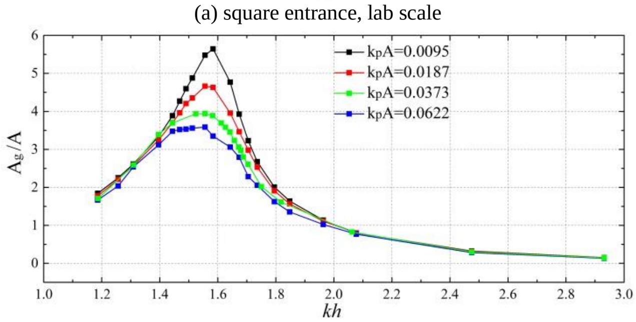
Table 2. Frequencies corresponding to the peaks of amplitude response curves with different incident wave steepness.

In order to investigate gap resonance as a function of wave steepness, simulations were run with incident wave amplitude A ranging from 0.003m to 0.025m or wave steepness k_pA ranging from 0.0093 to 0.0852, where k_p is the wave number corresponding to the maximum amplitude response. The amplitude response curves of the surface elevation in the gap for the three different entrance shapes are shown in Figure 5. It is found that nonlinear effects are pronounced near the resonant frequency region and gradually decline as the frequency shifts far away from the resonant region. The dependency of resonant amplitude and frequency on wave steepness is summarized in Figure 6 and Table 2, respectively. From these results it is obvious that steeper waves result in smaller wave amplification in the gap. More specifically, the wave amplification is reduced by 43.43% and 36.35% for square and bilge keel entrances, respectively, when the incident wave steepness is increased from 0.0093 to 0.0634. With respect to resonant frequency, both configurations experience little change.

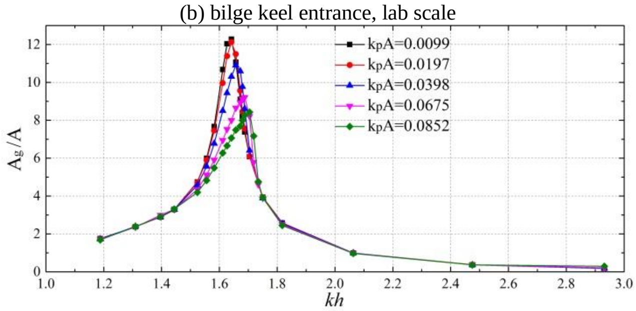
By contrast, for the rounded entrance there is little change in both resonant amplitude and frequency when wave steepness is increased from 0.0099 to 0.0197. However, when the wave steepness is further increased the trend in resonant amplitude is similar to that observed for the square and bilge keel entrances, whereas the resonant frequency will evidently shift to higher frequency zone with RAO curves evidently bending to the right side. To explain these results contours of vorticity close to the resonant frequency are shown in Figure 7 for the rounded case. All the subfigures in Figure 7 are captured at the same instance right after the free surface reaches the lowest level. Figure 7(a) and (b) indicate that vortex shedding is absent near the inner corners and hence the damping in the system is expected to be dominated by wall friction. Furthermore, since there is very little change in resonant amplification of the elevation in the gap at these wave steepness it appears that the wall friction is a linear function of surface elevation or the vertical velocity within the gap (since this is proportional, through the free surface boundary condition, to the free surface elevation).



(a) square entrance, lab scale



(b) bilge keel entrance, lab scale



(c) rounded entrance, lab scale

Figure 5. Amplitude response curves of free surface elevation in the gap with different wave steepness.

In contrast to the results at small incident wave steepness, when the incident wave steepness is increased to 0.0398 small vortices are observed to shed from the rounded corners in Figure 7(c). For even larger wave steepness of 0.0675 in Figure 7(d), the vortices shed from the rounded corners become larger. Collectively these results suggest that at larger wave steepness losses associated with flow separation at the entrance to the gap augment losses due to wall friction. Since entrance losses in hydraulics are known to depend on the dynamic pressure (i.e. the square of the velocity in the pipe) it is therefore expected that the damping affecting the oscillatory motion of the water in the gap will become increasingly non-linear at higher wave steepness. Noting that Vinje [10] deduced that for a sufficiently narrow gap the free surface motion within the gap may be described in terms of a single degree of freedom oscillating system, this non-linear damping would be expected to result in an increase in the frequency corresponding to the maximum response as the incident wave amplitude (i.e. the driving amplitude of the oscillator) increases. Equally the relative amplitude of the free surface motion in the gap would be expected to decrease with increasing incident wave steepness. Both of these expectations are consistent with Figure 5(c).

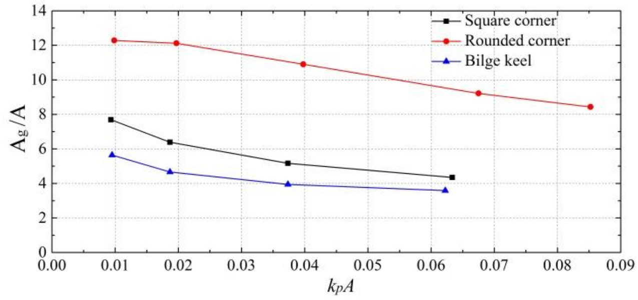
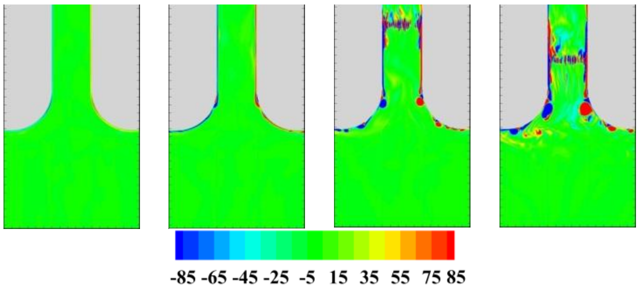


Figure 6. Dependency on wave steepness of resonant amplitude with different entrance shapes.



(a) 0.0099 (b) 0.0197 (c) 0.0398 (d) 0.0675

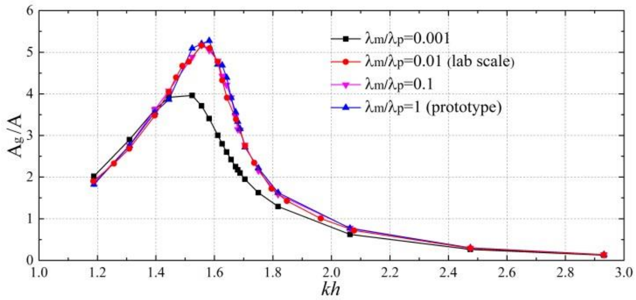
Figure 7. Vortex structures with different wave steepness k_pA.

Scaling Effect

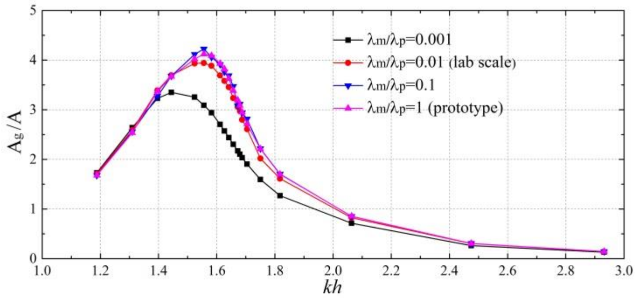
Test condition	Square	Bilge keel	Rounded
$\boldsymbol{\lambda_m/\lambda_p}$= **0.001**	kh = 1.52	kh = 1.44	kh = 1.61
$\boldsymbol{\lambda_m/\lambda_p}$= **0.01**	kh = 1.56	kh = 1.56	kh = 1.66
$\boldsymbol{\lambda_m/\lambda_p}$= **0.1**	kh = 1.56	kh = 1.56	kh = 1.70
$\boldsymbol{\lambda_m/\lambda_p}$= **1**	kh = 1.58	kh = 1.56	kh = 1.70

Table 3. Frequencies corresponding to the maximum responses of amplitude response curves with different scales.

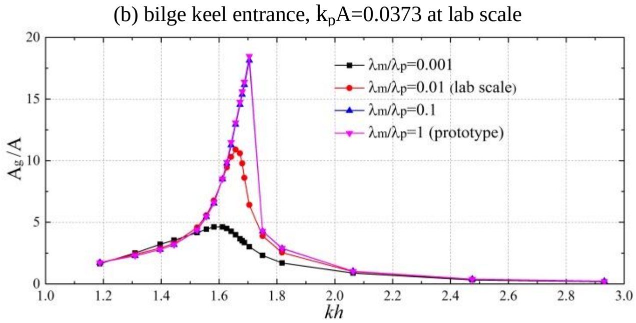
The above results are representative of 'lab' scale. In general, however, it is helpful to study how experimental results relate to more representative scales encountered in engineering practise. To investigate these scaling effects four different scales have been simulated with scaling factor λ_m/λ_p ranging from 0.001 to 1, where λ_p and λ_m refer, respectively, to the prototype and the model scale adopted in the present study. The amplitude response curves for the different entrance shapes at various scales are displayed in Figure 8, and the dependency of resonant amplitude and frequency on scaling factor are summarized in Figure 9 and Table 3, respectively. As for the square corner it can be seen that being equal or larger than the lab scale (λ_m/λ_p= 0.01), the scaling effect is of minor influence and all the response amplitude curves are similar. Nevertheless, when the scaling factor is decreased to 0.001, the viscous damping will play a relatively more important role. As a result, a reduction in both resonant amplitude and frequency can be found in Figure 8(a). While the bilge keel setup has the same trends as its square counterpart, the rounded counterpart is distinguished from the other two setups by its distinctive features at lab scale. Increasing the scaling factor from 0.01 to 0.1, dramatic scaling effect is present that the response amplitude curve sees an increase in both resonant amplitude and frequency. It is also noteworthy the viscous damping is dominating when the scaling factor is decreased to 0.001, which even renders the resonant amplitude comparable with the other two counterparts as shown in Figure 9. Besides, the resonant band width is evidently reduced with increasing scale due to the reduction in viscous damping.



(a) square entrance, k_pA=0.0373 at lab scale



(b) bilge keel entrance, k_pA=0.0373 at lab scale



(c) rounded entrance, k_pA=0.0398 at lab scale

Figure 8. Response amplitude curves of free surface elevation in the gap with different scales.

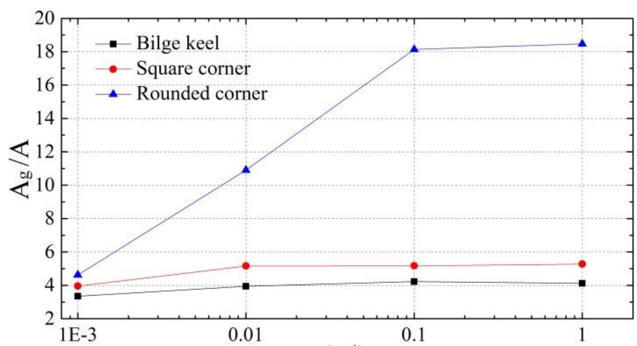


Figure 9. Dependency on model scale of resonant amplitude with different entrance shapes.

On balance, the scaling effect is more significant for cases with rounded corners compared to square corners or bilge keels. For this reason, conducting wave tank tests for configurations with square corners and bilge keels may provide satisfactory predictions applicable for real life situation. However, it may be more difficult to predict the response for rounded corner configuration in a certain range of scale with certain radius to gap width ratio.

Concluding Remarks

This paper investigates a two-dimensional gap resonance problem of two fixed boxes in side-by-side configuration. The nonlinearity of free surface elevation in the gap was studied by varying the incident wave steepness. The results show that the amplitude response for the free surface elevation in the gap contracts and the frequency corresponding to the maximum response increases with increasing incident wave steepness. The "Duffing-like behaviour" can be related to nonlinear damping caused by flow separation. In addition, the scaling effects may be more difficult to predict when the nature of the damping is different in the experiments to that expected in the prototype.

Acknowledgments

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