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An experimental and numerical study of the vortex shedding dynamics during gap resonance

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1 Introduction

For side by side offloading of Liquid Natural Gas (LNG) or berthing of ships next to solid terminals the hydrodynamic resonance of the free surface in the narrow gap can govern operability [1]. Near resonance, the potential flow damping is small and viscous effects can provide a significant contribution to the total hydrodynamic damping. A viscous treatment is therefore necessary in order to predict the free surface amplitude accurately. However, compared to the inviscid response, the viscous effects are challenging to model. Experiments or computational fluid dynamics (CFD) with high spatial and temporal resolution are generally necessary for their prediction, as well as to obtain damping coefficients which often form the basis of efficient predictive models adopted by industry.

Provided that the bilge edge is sufficiently sharp, flow separation and vortex shedding may be expected to have a dominant contribution over other viscous effects such as skin friction. However, compared to the flow around an isolated edge, such as that considered by Graham [2] for instance, the gap resonance problem presents additional complexities due to asymmetry between the entrainment and expulsion of the flow out of the gap. Additionally, the confinement of the vortex shedding can also result in a highly turbulent flow, leading to enhanced mixing and dissipation. While several studies have investigated the free surface amplitudes associated with the gap resonance problem, the flow field around the bilge and in the gap has not been extensively investigated [1]. High quality experimental investigations are warranted in order to establish the capabilities of measurement techniques such as Particle Image Velocimtery (PIV) to resolve these highly dynamic flow structures as well as to provide an essential means of validation for numerical models.

To this end, the objective of this study is to design an experiment to study the flow field and vortex shedding dynamics near the bilge during gap resonance, in order to evaluate the capabilities of PIV and CFD for their prediction. We investigate the response associated with regular waves incident to a 2D section of a fixed barge located next to a vertical wall. The set up is considered to be a suitable analogue for a LNG carrier positioned side by side to a deep draft floating LNG facility or a ship berthed next to a stationary terminal.

2 Experimental Set-Up

The experiment was conducted in the wave tank at Ecole Centrale Marseille. The wave tank is 16.77 m long, 0.65 m wide and the water depth was set at 0.52 m. The barge had a beam of $b = 0.6$ m, draft of $d = 0.12$ m and spanned the width of the tank. An impermeable vertical wall was located at a distance of 12 m from the wavemaker and the gap between the barge and the wall was 0.0728 m. A piston-type wavemaker was used to generate regular waves. The water surface elevation was measured at several locations upstream of the barge as well as in the gap. The flow field around the bilge closest to the wall was captured using a PIV system which comprised two 50 mj lasers pulsed at 100 Hz. The acquisition was set to 200 Hz by adjusting the interval between the two laser pulses. A Phantom V641 camera with a resolution of 2560x1600 pixels was synchronized with the laser pulses. The water was seeded with silver coated hollow glass spheres of around 10 to 14 μm in diameter. Three different fields of view were considered, as listed in Table 1. The field was centred each time on the corner of the barge.

Table 1: PIV setup

Field size (cm^2)	29.6×18.5	18.2×11.4	9.6×6.0
Pixel size (cm/pixel)	0.0116	0.0071	0.0037

3 Numerical Modelling

Numerical results were computed in 2D using a finite-volume based solver for the unsteady Navier-Stokes equations. The domain was equivalent in dimensions to the experiment. The computations were performed using a fully structured mesh which was refined around the free surface, the barge walls and the vertical wall. The barge walls and the vertical wall were modelled as no-slip boundaries and the upper boundary of the domain was set as a pressure-outlet. Regular waves were generated at the inlet with a linear ramp function applied to the wave height for the initial 3 wave periods, as implemented in the experiment. The flow field was computed with no turbulence model (i.e. using direct numerical simulations) and the free surface was modelled using the Volume of Fluid approach. The computations were performed using a constant time step of T/1000. The velocity field around the bilge closest to the wall was sampled at a rate of T/200 for comparison with the PIV.

4 Results and Discussion

The response of the free surface in the gap between the barge and vertical wall is first demonstrated, given its role in driving the vortex shedding around the bilge. Figure 1 shows the measured response amplitude operator RAO (A_{gap}/A_i) as a function of wave period, for constant steepness in which the resonant wave period of approximately T=1.1 s is clearly identifiable. Also shown are the RAOs as a function of steepness, for a constant wave period of $T = 1.1$ s associated with the maximum response. The results have been compared with the model by Kimmoun et al. [3]. Favourable agreement is demonstrated when employing a quadratic damping coefficient of $C_{d,lid} = 1.4$, which was obtained by tuning iteratively to the peak response. For these cases the contribution from linear damping (e.g. Stokes boundary layers) was found to be negligible.

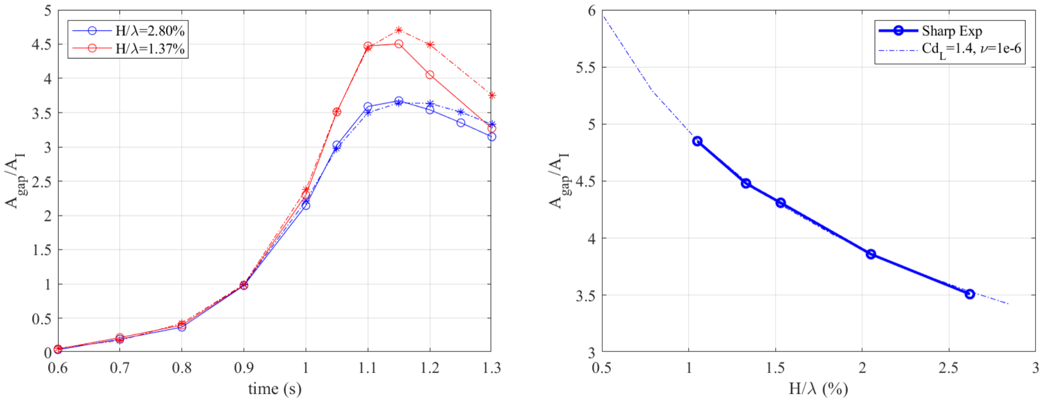

Figure 1: (Left) Free surface RAO in the gap as a function of wave period for wave steepness values of $H/\lambda = 1.37\,\%$ (red) and $2.80\,\%$ (blue). (Right) Free surface RAO as function of wave steepness for $T = 1.1$ s. The measurements are compared to the model by Kimmoun et al. [3] with $C_{d,lid} = 1.4$.

The time histories of the maximum and minimum vorticity measured in the gap are presented in Figure 2. These show the evolution of the gap resonance as it tends towards a quasi-steady state. Results are presented for 4 separate tests with equivalent wave conditions; 2 performed with the measurement window near the end of the barge (i.e. adjacent to the side of the tank) and 2 at near the centre of the barge. A generally high degree of repeatably and spatial invariance in the flow dynamics along the span of the barge is demonstrated. An asymmetry between the direction of the flow is also evident, with the maximum absolute vorticity observed during the ejection of the flow out of the gap and shedding of a vortex rotating in the clockwise sense.

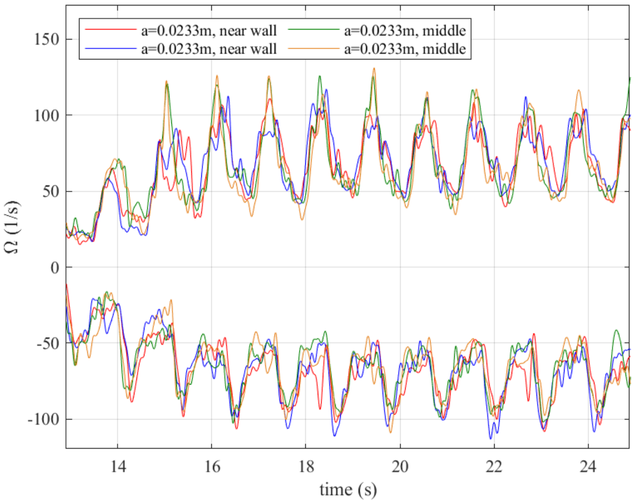

Figure 2: Time histories of maximum and minimum vorticities in the gap for a wave amplitude of $a = 0.0233\,\mathrm{m}$ $(H/\lambda = 2.6\,\%)$, measured near the wall and centre of the barge. Each position is repeated twice.

To illustrate the vortex shedding dynamics once the resonance has obtained an approximate steady-state, contours corresponding to the maximum vorticity as measured using PIV are shown in Figure 3. The vorticity results were found to be highly sensitive to the resolution of the velocity field. To demonstrate this, the results have been presented for the various pixel sizes listed in Table 1. The maximum vorticity is shown to increase when the resolution is increased as finer details of the vortex sheet were able to be resolved.

The numerical results obtained using CFD are shown in Figure 4 for comparison. These have been computed for three different mesh sizes in order to assess the sensitivity of the vortex shedding dynamics to the mesh resolution. For these cases the maximum vorticity occurs within the boundary layer. The numerical results agree qualitatively with the measurements, particularly in relation to the position of the vortex core. The finding that the magnitude of the vorticity is greater compared to the PIV measurements suggests that the PIV was unable to fully resolve the flow within the boundary layer.

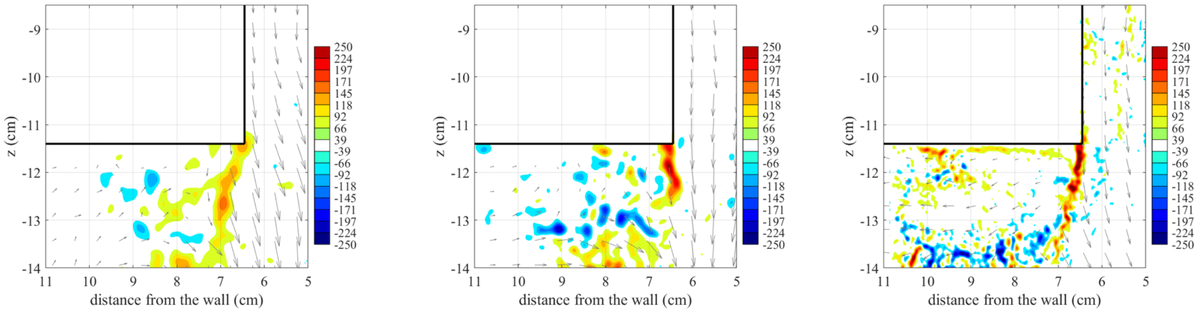

Figure 3: Vorticity field corresponding to maximum velocity as measured using PIV with three different resolutions.

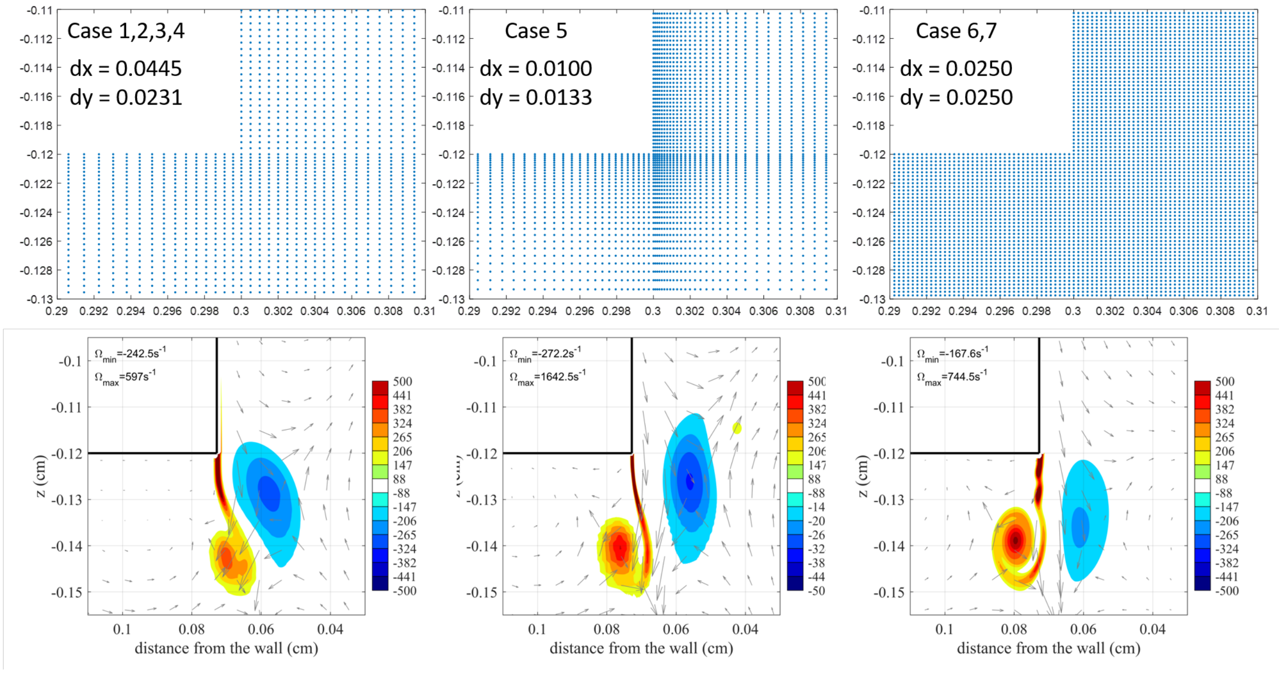

Figure 4: Vorticity field corresponding to maximum vertical velocity as computed using CFD with three different mesh sizes.

Acknowledgment

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