Circular cylinder impact on curved water surfaces

Arefhossein Moalemi[1,2*], Henrik Bredmose[1], Amin Ghadirian[1], and Trygve Kristiansen[2]

[1] *DTU Wind Energy, Nils Koppels Allé, Building 403, DK-2800 Kgs. Lyngby, Denmark*
[2] *Department of Marine Technology, Norwegian University of Science and Technology, Trondheim, Norway*
aref@dtu.dk hbre@dtu.dk amgh@dtu.dk trygve.kristiansen@ntnu.no*

1 Introduction

Slamming pressures from breaking waves are associated with strong stochastic variation. Accordingly, the force time history for even nominally identical waves may represent a significant variability given the stochastic nature of wave breaking. Although the time-integrated force (impulse) is expected to show smaller variations than the pressures (Ghadirian and Bredmose [2019]), understanding of the causes or basis of the variability is still important. One possible explanation is associated with the transverse instability of the breaking wave front, which leads to un-even pressures at impact. Further, if the water surface and body surface are almost parallel, a rapid air flow will be driven in the closing gap, which through the shear-instability can perturb the free surface shape. As a third phenomena, it is known that in the early stage of water entry of objects, the airflow creates an initial depression of the free surface. If the shape of the bottom of the body is of low curvature, a noticeable volume of air can be trapped between the object and the water Reinhard et al. [2016]. Wilson [1991], and Howison et al. [1991] demonstrated that the trapped air has high pressure, which affects the hydrodynamic load on the body.

Impact with a non-flat water surface can be characterized by the curvature of the local perturbations. In the present study, we investigate the effect of surface curvature on the impact loads in a generic two-dimensional setting, where a circular cylinder impacts vertically on standing waves. Only a few studies of water entry has looked into the effect of surface waves on the impact loads. Sun et al. [2015], used the boundary element method to analyze a two-dimensional wedge entering first-order Stokes waves. He found that the wavy free surface causes a noticeable difference between the pressure distribution of the wedge's two sides due to the incident wave's velocity. Also, he showed that changing the wave characteristics can increase or decrease the pressure magnitude on the wedge.

In our study, a standing wave was used to represent the wave front instabilities of interest in general impacts. The standing wave was chosen to eliminate the unequal pressure distribution on the cylinder that would occur for progressive waves. The wave phase was adjusted such that the cylinder would impact symmetrically on crests or troughs of the standing wave, at the point in time of maximum crest or trough amplitude. Next, by changing the wave length, amplitude and crest/trough impact type, the curvature effect on the loads was studied.

We here show initial results for impacts at crests and troughs, for a case where the free surface curvature is close to that of the cylinder. This limiting case is interesting since the wetted area is large for the trough case. We next show results for varying wave amplitude and discuss the loads in terms of added mass and growth of wetted area.

2 Experimental set-up

The experiment was carried out in the 'Ladertanken' laboratory at NTNU's Tyholt campus. Ladertanken consists of a wave flume tank with dimensions 13m × 0.6m × 1.3m. The tank is provided with a single flap type wave generator. A movable cross-wall was installed downstream of the wavemaker to reflect the traveling waves and produce standing waves with different amplitudes and wave length. Seven wave probes were used to precisely measure the wave amplitude. The test model was a half-cylinder with a diameter of 0.3 m, and a length of 0.59 m, fitted to the lateral width of the flume. The cylinder was connected to a wooden box which was connected to the rig top frame (triangular aluminum frame) visible in figure 1. This frame was connected via a force transducer to a ball-screw type vertical actuator. Four inertia based accelerometers were used to measure the dynamic response of the structure during impact.

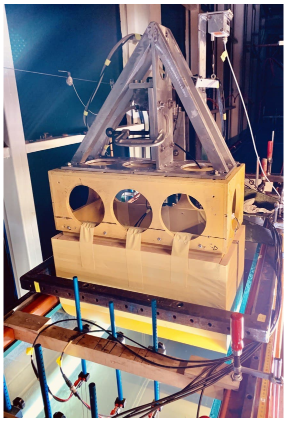


Figure 1: Test model

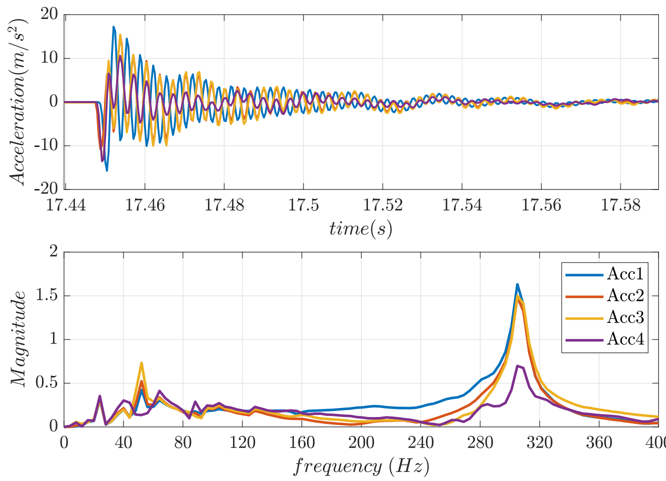
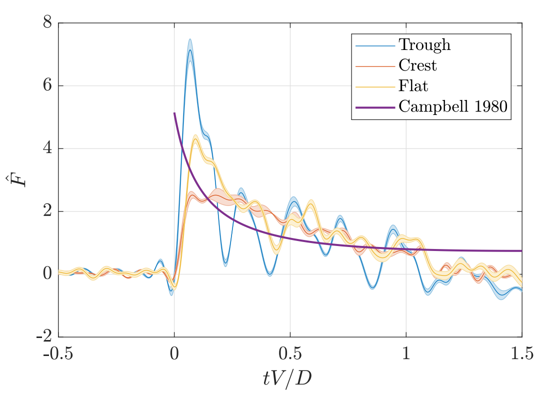


Figure 2: Hammer test data

Prior to the main tests, pluck tests were conducted to find the natural frequencies of the system. An example of such a test is shown in figure 2. Four peaks under 100 Hz are noticeable. The first peak at 25 Hz is related to the vibration of the ball-screw member. The second, third, and fourth peak at 42 Hz, 65 Hz, and 102 Hz are related to the vibration of the aluminium frame, wooden frame, and support structure. The largest peak at a frequency of 302 Hz is related to the vibration of the screws which connected the model to the ball-screw member. The rig's total stroke is 40 cm, and the cylinder's maximum constant velocity just before the water entry was 0.7 m/s. A Photron FASTCAM SA-X2 high-speed camera, operating at 2000 frames/s, was installed in front of the half-cylinder base for visualization.

3 Impacts on flat surface, crest and trough

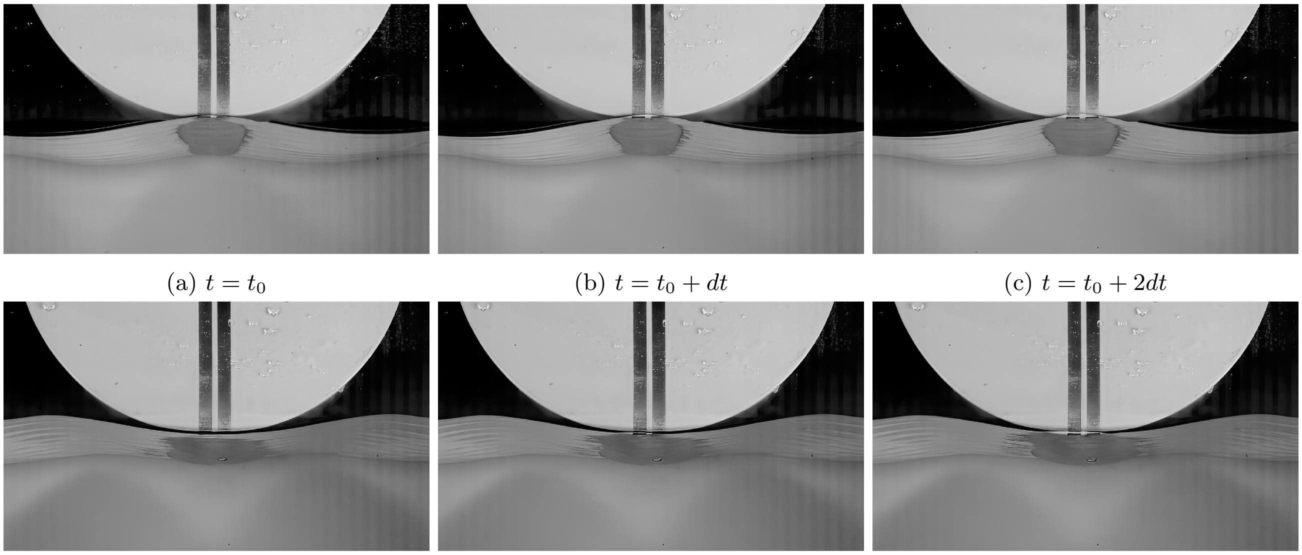
Time histories of cylinder impact on a flat surface, a crest and a trough are shown in figure 3. A wave length of $\frac{\lambda}{R}$=0.833 was used, where R is the cylinder radius. This corresponds to a wave frequency of 2.5 Hz. Lateral instabilities in the flume made shorter waves in-achievable. The wave amplitude was 8 mm.



(a) $\frac{\lambda}{R}$=0.833 A=8 mm

Figure 3: Effect of wave phase on the impact magnitude

The cylinder hydrostatic force and dynamic response of the system were subtracted from the raw force data to obtain the hydrodynamic force on the cylinder. A low pass filter with a cut-off frequency of 90 Hz was applied to eliminate the effect of high frequency noise. Because of the high frequency of the standing waves, each test was repeated at least ten times. The curves in the figure represent the average value from the tests and also mean



(a) $t = t_0$ (b) $t = t_0 + dt$ (c) $t = t_0 + 2dt$

(d) $t = t_0$ (e) $t = t_0 + dt$ (f) $t = t_0 + 2dt$

Figure 4: Image(a) shows the cylinder impact on the wave crest at $t = t_0$. Image (b) and (c) show the cylinder wetted area after one and two-time steps. Image(d) shows the cylinder impact on the wave trough. It is visible that the wetted area's growth in the image(e) and (f) is larger than the image (b) and (c).

plus/minus one standard deviation from the ten repetitions. There is a substantial fluctuation right after the force peak in the trough and flat water entry plot. These oscillations were caused by the experimental setup, and the frequency of them is 25 Hz. However, these fluctuations are deterministic, and they show strong repeatability, as evident by the averaging process. From the force curves, it is evident that the slamming loads for the impact on the wave trough is larger than the impact on the wave crest and flat free-surface figure 3. Campbell [1980] experimental slamming coefficients (1) for water entry of a circular cylinder was used for comparison in the figure:

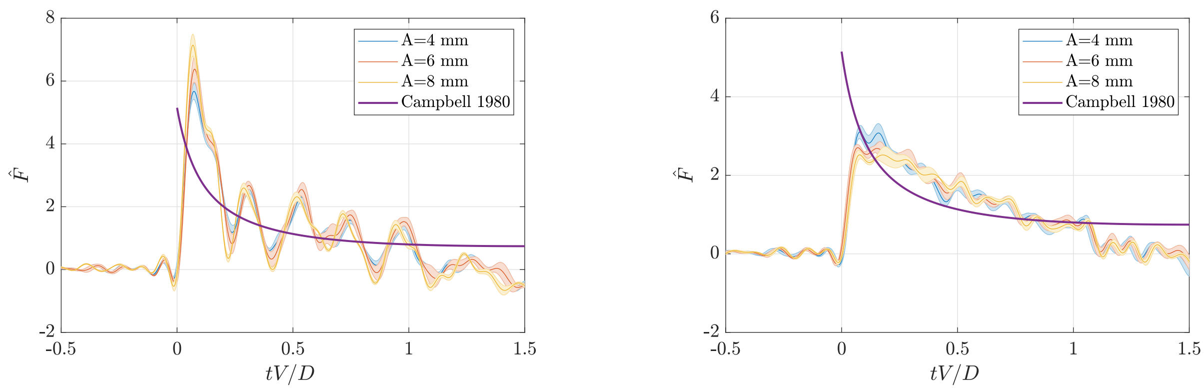
$$C_S = \frac{5.15}{1 + \frac{19h}{D}} + 0.55\frac{h}{D}, \frac{h}{D} < 1 \tag{1}$$

Here D and h are the cylinder diameter and the submergence of the cylinder cross-section relative to calm water level. The difference in impact magnitude can be linked to the impact area and added mass at the initial impact. When the cylinder hits a crest, the impact area is small, and the cylinder has to displace a smaller volume of water at the early stage of impact. On the contrary, when the cylinder hits a trough, its contact area is more extensive, and a larger amount of water has to be displaced. This acts to increase the load on the cylinder. Figure 5 shows the early stages of the cylinder entry at the wave trough and wave crest. In frame (a) and (d), we can see that the contact area is more extensive when the cylinder reaches the wave trough. Moreover, in the wave trough impact, the wetted area's growth is larger than for the wave crest impact. This increases the water volume the cylinder has to displace and thus adds further to the trough impact loads.

4 Effect of wave amplitude

As shown in the previous section, the free surface curvature significantly affects the impact load. The wave amplitude and wavelength are the two parameters that define the standing wave's curvature. A series of tests with varying wave amplitude was therefore conducted. The wave length was kept at the previous value of $\frac{\lambda}{R}$=0.833.The wave amplitude was taken as 4, 6 and 8 mm, respectively.

From the results of figure 5a, larger wave amplitude enhances the slamming loads for the trough impacts. This is readily linked to the added mass at initial impact and the growth of wetted area during impact. By increasing the wave amplitude, the cylinder's curvature and free surface become more similar to each other. As a result, in the early stage of impact, the wetted area will increase, and the cylinder has to displace more water, which leads to a higher force on the cylinder. In contrast, when the cylinder hits the wave crest 5b, increased wave amplitude leads to a smaller initial added mass and a less rapid growth of the wetted area. Consequently, the volume of water that the cylinder has to displace to enter the water is smaller for the higher amplitude.



(a) $\frac{\lambda}{R}$=0.833, Trough (b) $\frac{\lambda}{R}$=0.833, Crest

Figure 5: The effect of wave amplitude on the impact magnitude

5 Discussion

We have made generic tests to demonstrate surface curvature's effect on the impact loads from a circular cylinder. Although the measurements involve structural oscillation, the load increase from the impact in a trough and the reduction by the impact on a crest is clearly demonstrated by the results. These observations are readily linked to the added mass of the water at initial impact. The limiting case of almost equal curvature between the cylinder and the wave trough has thus been found to give the largest loads. Preliminary reproduction tests with a free surface CFD solver have been conducted and will be used in the future to extend the study to the parameter space of also shorter waves, where multiple wave crests are hit during the impact.

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