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An experimental study of slamming impact during forced water entry

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Abstract

Water impact problems have received considerable attention from both mathematical and engineering sciences, because of their significance in many practical applications such as ship hydrodynamics and ocean engineering. The characteristic feature of the water impact problem is the resultant hydrodynamic impacts usually referred to as slamming.

The paper reports on experiments done on a 5º wedge entering water at a constant velocity. This is accomplished by driving the wedge using an actuator programmed to execute triangular wave trains. Pressures are measured using sensitive transducers at a high sampling frequency. Results are compared with established theories and reasonable agreement is found

Introduction

Pressure distribution over a wedge vertically entering water (Fig. 1) has been of interest in the field of ship building for both structural design and seakeeping properties. This problem is a precursor to the understanding of the problem of slamming of ship hulls in water. As marine technology advances in the areas of propulsion and materials, boats are being designed with the ability to travel at significantly higher speeds. In practical conditions the ability to predict the response for various sea states is required for efficient design.

Several theoretical models for slamming pressures on a body have been developed over the years. One theoretical method that was developed from first principles was by Wagner [1]. The solution is restricted to the initial stage of water impact and assumes that the body shape close to contact point has a small deadrise angle and the free-surface elevation is of the same order as the penetration depth. These restrictions make it possible to linearize the boundary conditions and to impose them on an initially undisturbed free surface. The solution is found from the velocity potential for a flat infinitely long plate moving with a velocity V perpendicular to its surface and with an expanding width $2c(t)$. Combining this with the Bernoulli equation the pressure distribution is identified as

$$p(x,t) = \rho V \frac{c(t)}{\sqrt{c(t)^2 - x^2}} \frac{dc}{dt} \qquad (1)$$

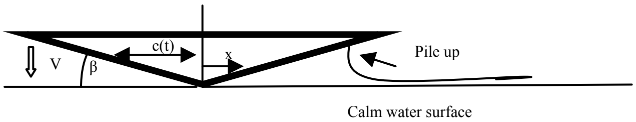


Figure 1: Parameters involved in the description of the water impact of a wedge.

Where

$$c(t) = \frac{\pi}{2} \frac{Vt}{\tan\beta} \qquad (2)$$

Eq. 1 is only valid for $x < c(t)$. However it is well known that Wagner's solution has a singularity at the intersection between the body surface and the water surface, which makes the numerical solution for a general shape of body difficult. Yettou et al [2] in their recent paper aimed at achieving a better understanding of the water loading and hull pressures experienced by a planing boat repeatedly impacting waves and noted that the time scale during an impact of solid body entering water is rapid, typically lasting only milliseconds. Their equation for maximum pressure on the wedge is given by:

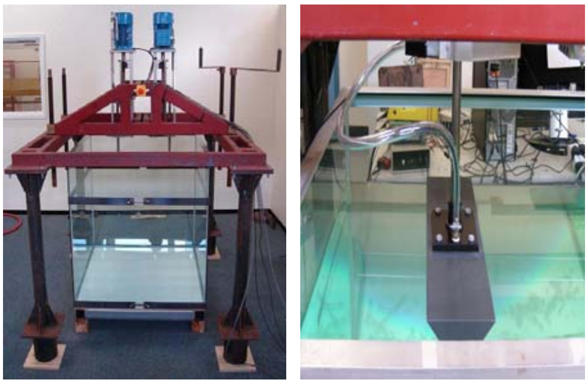
$$P_{\max} = \frac{1}{2}\rho\left(\frac{dc}{dt}\right)^2 \left[\cos^{-2}\beta - \frac{V^2}{\left(\frac{dc}{dt}\right)^2}(\sin^2\beta)\right] \qquad (3)$$

Judge et al [3] carried out an investigation into the vertical and oblique (transverse velocity) wedge entry into water for both symmetric and asymmetric wedges however no pressure or acceleration data are presented. Wu et al [4] presented experimental and numerical results for a free-falling wedge into water, and reported good agreement with the numerical model.

When conducting slamming impact experiments, pressure transducers are used to measure the short duration impact pressures at very high sampling frequency. The sensitivity of the pressure transducer can change over time due to general wear and tear and degradation of the piezo-crystal. Hence, the transducer may become less sensitive as micro cracks that develop within the crystal and propagate. The accuracy of these pressure transducers is ensured by regular calibration with established theories. It is important to note that all theories are set up for a constant velocity during impact, which is hard to achieve in a free falling wedge test. Our paper uses an actuator to drive a wedge into water at a constant velocity. The pressure during impact is compared with theories in this paper

Experimental Setup

The existing Planar Motion Mechanism (PMM) facilities in the UWA Hydrodynamics Laboratory were utilized to carry out the experimental program. Experiments were conducted in a rectangular tank of 1x 1 x 1m. The water depth in the tank for this experiment is about 0.75m. A steel frame, with four legs extending to the edges of the rectangular tank, was used to support two stepper motors which were located above the tank, Fig. 2a. Linear bearing are used to convert angular motion into linear motion. The motors may be programmed to obtain strokes in the range of 0 – 200 mm and frequencies in the range 0 – 2 Hz. Because of the limited working range of the PMM motor, there is a natural decrease in maximum amplitudes at higher frequencies.



(a) (b)

Figure 2: Experimental setup for drop test experiment.

A wedge was attached at the end of the shaft of the actuator as shown in Figure 2b. The wedge was initially placed just above the free surface. As the motor produced a linear motion, the wedge penetrated into the water causing impact loads at the interface. The sensors attached to the wedge recorded the pressure along the travel path of the wedge.

To achieve constant velocity of penetration, V, we used a saw-tooth (triangular wave) signal as shown in Figure 3. Let A be the amplitude of the signal and T be the time period for one cycle. Then the velocity of the movement during downward penetration can be calculated as

$$V = \frac{dS}{dt} = \frac{4A}{T} \qquad (4)$$

A displacement transducer (LVDT sensor) fixed to the side of the PMM motor was used to measure the relative displacement between the motor and the oscillating shaft. A typical displacement time history is superimposed on the theoretical saw-tooth profile in Fig. 3. The profiles are reasonably similar, with a small variation between the upward and downward velocities. The frequency and amplitude of oscillation can be varied using the control system of the actuator. The test matrix is shown in Table 1.

A wedge of 45 deg was rotated to obtain a 5 deg wedge angle as shown in Fig. 4a. To measure the impact pressure, Kulite Semiconductors XML-8M-100 pressure transducers were selected for this experiment. Five pressure sensors which labels as P1, P2, P3, P4 and P5 were fitted at the bottom row and in the middle of the wedge in the slots provided as shown in Figure 4b. These transducers are located 7.5mm apart from the apex, starting with P1, P3, P4 and P5 respectively and P2 is 10mm apart from P1 in horizontal axis, the other sensors visible in Figure 4b are not used. The pressure sensors were connected to the data acquisition system via an interface board to the DAQ. Agilent U2351A USB DAQ device was used to collect experimental data at 37 kHz for post processing and comparing results with the corresponding theory.

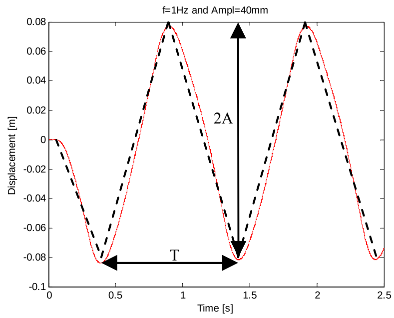


Figure 3: Triangular input signal producing constant velocity. (---) Actual and (—) Experiment.

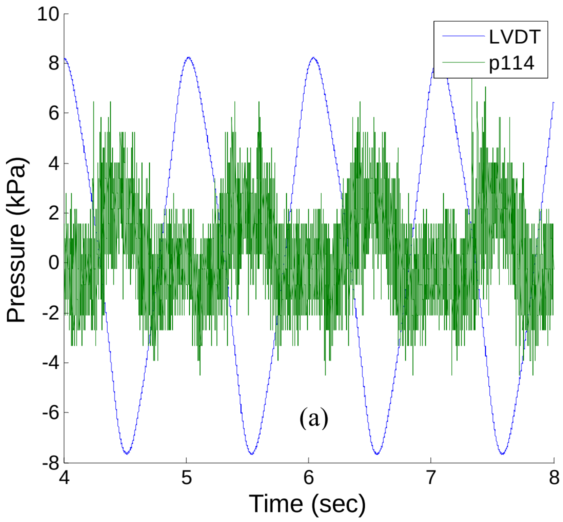
Table 1: Test matrix

Run No.	Amplitude (mm)	Frequency (Hz)	Velocity (m/s)
1 to 15	38.33	0.97	0.148
1 to 15	26.27	1.75	0.184

Figure 4: Photo graph showing (a) the wedge at 5° angle (with insertion block) and (b) pressure sensors position

Results and Discussion

Figure 5 shows typical pressure measurement (kPa) for the two velocity cases. The time history for one pressure sensor is shown against the displacement. The pressure data at the lower velocity is noisy and the peaks are not very clear. In contrast, impact peaks are readily observable at the higher velocity. The free surface was noticeably disturbed after the first impact and the disturbance was reflected off the walls causing subsequent peaks to fluctuate in magnitude. Different types of perforated mats were attached to the side walls to reduce the reflection. However, only the first cycle data was used for subsequent analysis.



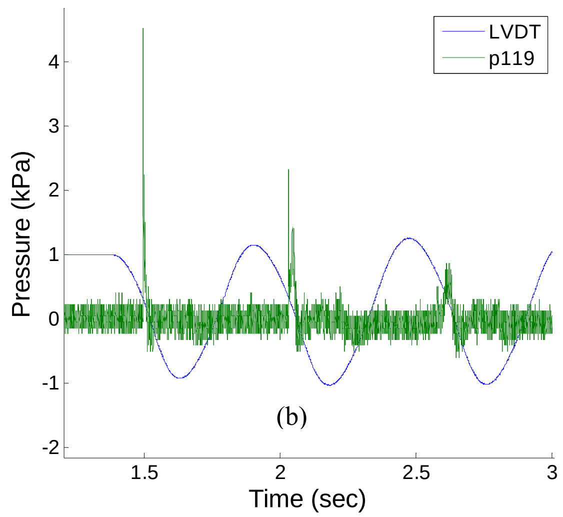


Figure 5: Experimental plot (a) 1Hz, amplitude of 40mm and (b) 1.8Hz, amplitude of 28mm.

Figure 6 shows four snapshots of the wedge penetrating the water, at 10ms interval from left to right. These pictures were captured by a high speed video camera operating at 1000 frames per second. The wedge was moving at 1Hz and 40mm amplitude. As the wedge enters the water, some jet formation is observed, which may affect the measurements of the outer most sensor (P5).

A plot of Wagner theory Eq (1) versus experimental results is shown in Figure 7. From Eq (1), the magnitude of the pressure is infinite when $c(t) = x$. Truncated values of the pressure peak can be obtained when time is incremented by 1/sampling frequency. The magnitude thus obtained depends to some extent on the sampling frequency and sensor position. We believe that this provides for a realistic comparison with experiments. The Wagner pressure profile agrees well with the experimental data along the time axis. Some variations are noted at the higher velocity of 0.2 m/s. At the lower velocity, magnitude difference in pressure peak is about 60%, while at the higher velocity, the error reduces to 10%.

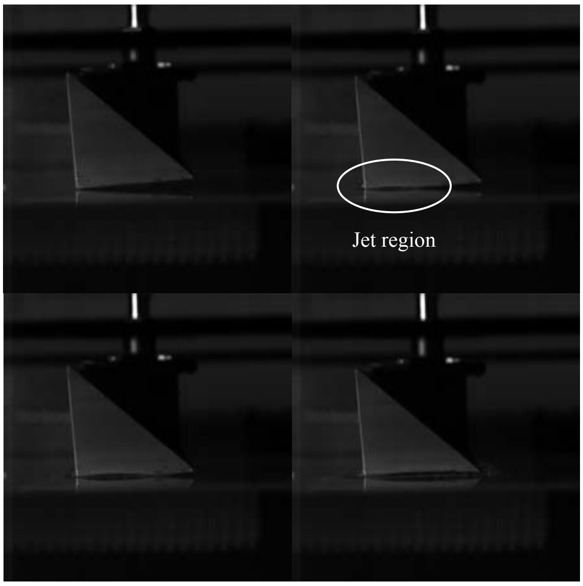
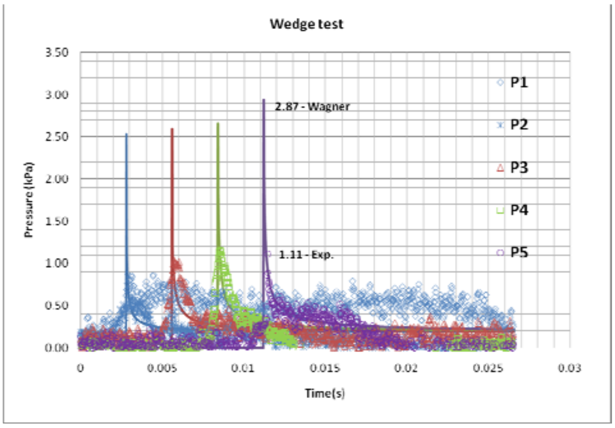


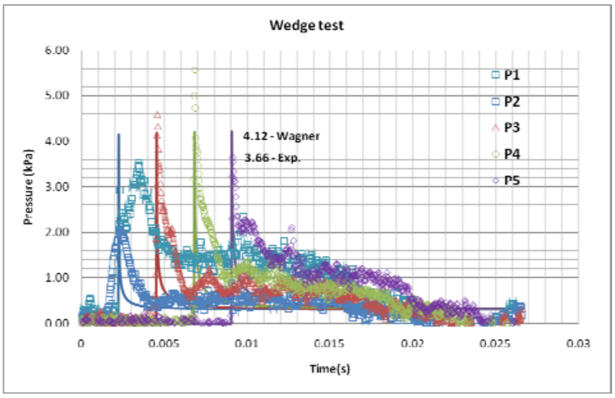
Figure 6: High speed video captured at 1Hz, amplitude of 40mm. From left to right, moment P1 just touch the water surface and jet formation around P5 at 10ms later.

The duration of the impact of solid entering water can be very short, typically in a few milliseconds. Due to disturbed water surface after the first cycles, the position and magnitude of the pressure, time duration are difficult to measure accurately. To obtain an approximate mean pressure, several repeat tests were performed. For each of the 15 runs and for each pressure sensor, mean pressure of the first cycle and its standard deviation are reported in Table 2. Also shown are the pressures calculated from the formulae of Wagner (Eq. 1) and Yettou et al. (Eq. 5). These results are shown pictorially in Fig. 8. The error bars on the two figures are obtained from table 2 and is set to an equivalent of ±0.3kPa and ±2kPa standard deviation, respectively. A line drawing across the data points and fall within the error bar, suggesting that the repeated run is within the range of pressure impact for that particular condition.

At lower velocity, the mean pressure seems to be approximately around 1kPa. The pressure fluctuation is around 0.3kPa, which indicate the pressure variation is close to the mean pressure. Upon increasing the velocity, the mean pressure raises to 4kPa and the fluctuation of the pressure seems to be approximately 2kPa. At lower velocity, the agreement with theory is quite poor, while a marked improvement is seen at higher velocity. Our results agree well with Wagner's theory to within 10%. Yettou's result seems to predict higher pressures than seen in the experiment.



(a)



(b)

Figure 7: Wagner vs. Experimental plot for (a) 1Hz, amplitude of 40mm and (b) 1.8Hz, amplitude of 28mm

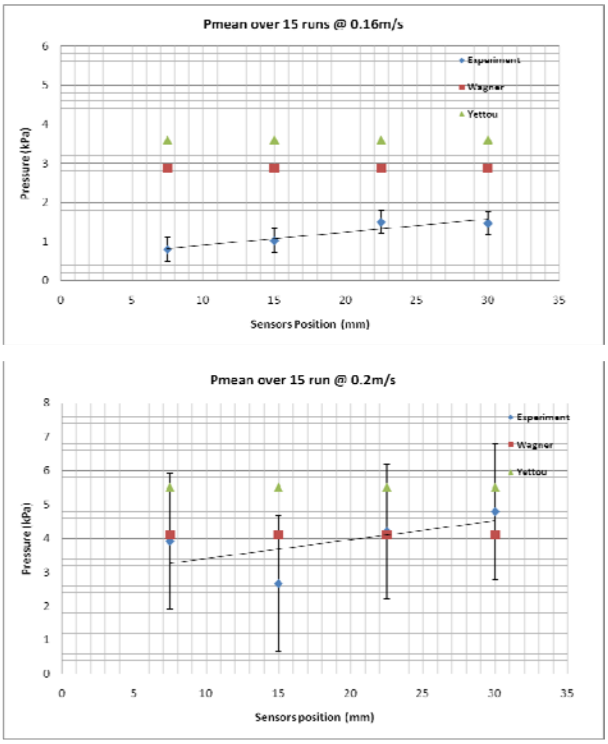


Figure 8: Pressure fluctuation during the 15 repeated tests at (a) 1Hz and 40mm Amplitude, (b) 1.8Hz and 28mm Amplitude

Table 2: Pressure in kPa

0.16m/s	**P1**	**P2**	**P3**	**P4**	**P5**	**Wagner**	**Yettou**
Mean	0.8	0.59	1.02	1.5	1.47	2.87	3.6
Std	0.26	0.18	0.32	0.53	0.37		
0.2m/s	**P1**	**P2**	**P3**	**P4**	**P5**	**Wagner**	**Yettou**
Mean	3.92	3.27	2.67	4.2	4.79	4.12	5.5
Std	2.07	2.53	0.97	2.17	2.67		

Conclusions

A specific set of experiments has been performed to study the phenomenon of impact pressure and dynamically calibrate the Kulite Semiconductors XML-8M-100 pressure transducers. A 5^o wedge was forced to enter water at a constant velocity by driving it with a programmable actuator. Pressures were measured along the sides of the wedge.

Experimental results obtained by repeating the tests showed a statistical variation of the maximum pressure recorded during the first cycle of impact. Within the limits of this variation, Wagner's theoretical model was found to agree well with the experimental data, especially at high velocity and small deadrise angle. The reasonable agreement between experimental data and the Wagner theory shows the merits of this constant velocity method. This constitutes simple and easily implemented way to study impact pressure and economic way to dynamically calibrate pressure sensors.

References

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