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EXPERIMENTAL INVESTIGATION OF SLAMMING LOADS ON A WEDGE

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ABSTRACT

This paper reports an initial series of wedge drop test results performed at Ocean Engineering Research Center (OERC) to investigate the slamming loads acting on a wedge of 10^0 deadrise. The aim is to get accurate two-dimensional impact loads to incorporate into the simulation of planing hull motion. Parameters varied in these drop tests were the mass of the wedge and the drop height. These factors were found to have negligible influence in predicting the maximum pressure coefficient. The analytical prediction method developed by Chuang [3] is found to be an accurate tool for determining maximum slamming pressures. In the future, more experiments could be performed varying the deadrise of the wedge to verify Chuang's [3] prediction method. Then this method could be implemented in the numerical simulation of planing hull motions in waves.

Key words: Slamming, Hydrodynamic impact, Simulation, Planing hull.

1. INTRODUCTION

The study of planing craft is closely related to the fundamental study of two-dimensional wedge impact problem. Von Karman [11] was one of the pioneer researchers in this field. He reduced 3D problem to 2D and simplified the cross section of floats of sea-planes to a wedge. He developed a theoretical model based on the momentum theorem and the water-added mass. His works were applied to the maximal pressure estimation on the floats of hydroplanes during sea landings. A similar study of two-dimensional water impact on solid bodies was conducted by Von Herbert Wagner [12]. Instead of considering a wedge, Wagner reduced the problem to dropping a plate on the water surface, considering that the virtual plate width varies over time. There is good agreement between the Wagner and the Von Karman formulae in the particular case of wedge entering water. Water Rise or Splash-up was not considered by Von Karman but Wagner took this into account by assuming some approximation. Payne [7] claimed that refinements added to Wagner's theory actually caused more offsets and the original Von Karman's theory is superior. He presented a model to calculate maximum pressure away from keel which is an improvement on Von Karman's theory. One of the first real drop tests with wedge-shaped models were conducted by Chuang [2]. The tests were performed with one rigid flat bottom model and five rigid wedges with deadrise angles of 1, 3, 6, 10 and 15 degrees respectively. The pressures were measured at the keel and away from the keel. The data from test results was used to provide a set of charts or empirical relations for estimating the maximum impact pressure due to rigid-body slamming of the wedges. It was concluded that the effect of trapped air needs to be taken into account for wedge angles between 0 and 3º. S.L. Chuang [3] & Stavovy [9] developed a prediction method for determining slamming pressures of a high speed vessel in waves. This method is based on the Wagner wedge impact theory, the Chuang cone impact theory and NSRDC drop tests of wedges and cones. Then he conducted some slamming tests of three dimensional models in calm water and in waves. The experimental results matched quite accurately with predicted results. Zhao et al. [15] presented non-linear boundary element method to solve water entry problem and verified the results with experimental drop tests of a wedge and a bow flare section. Engle & Lewis [4] conducted experimental drop tests and made a comparison between experimental results and several numerical methods relating to the maximum water-impact pressure of a symmetrical wedge for different initial impact velocities. Wu et al. [14] analyzed 2-D wedge free fall motion based on velocity potential theory. They compared the similarity solution and time domain solution with experimental drop test results. Breder [1] performed the drop tests to examine pressure loads on a rigid structure. He conducted the two-dimensional wedge drop tests with controlled vertical velocity, while earlier experiments involved free fall water entry problem. Peseux et al [8] used finite element method to solve highly non-linear hydrodynamic impact problem. A series of drop tests were conducted on rigid and deformable coneshaped structures. They validated their numerical results with experimental data. Yettou et al. [14] presented the results of experimental investigations of the pressure distribution on a free-falling wedge varying parameters such as drop height, the deadrise angle and the mass of the wedge. A thorough experimental investigation of constant velocity water entry problem has been performed recently by Tveitnes et al. [10]. They have provided some useful information relating to wetting factor, flow momentum drag and added mass based on those experimental data analysis.

2. THE EXPERIMENT

The experiments were performed in the deep tank of the Ocean Engineering Research Center (OERC) at Memorial University of Newfoundland. Only vertical drop tests were conducted varying the mass of the wedge and the drop height with the 10^0 deadrise model (Figure 2). The tests were conducted in calm water and the wind induced loading was negligible.

The detail of the experimental set-up is given in Mandeep et al. [5]. Still the instrumentation and data acquisition system is briefly described here for better understanding.

2.1 Description of the experimental set-up

The frame (Figure 1) used in the experiment was constructed using T-Slotted aluminum extrusions and was attached to the deep tank.

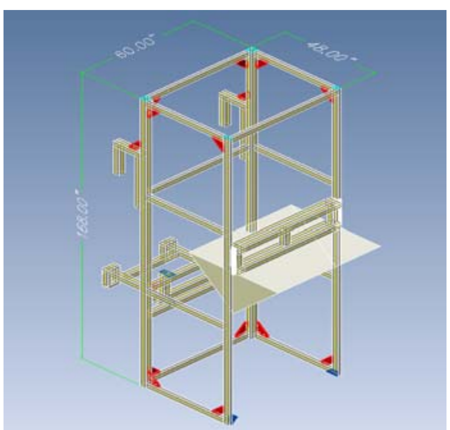

Figure 1. Front view of experimental frame with wedge attached to it (Ref. [5]).

The wedge apex was aligned perpendicular to the longitudinal axis of the tank. The wedge was attached to a trolley made of similar aluminum extrusions. This trolley slides on the guide rails fitted to the frame. The idea behind guide rails is to achieve high vertical drop speeds and high impact load bearing capacity. The linear motion guide rails have been custom designed from Macron Dynamics Inc. for these experiments [5].

The 10º deadrise model (Figure 3) was made from 0.5 inch thick clear acrylic sheets. The wedge has been specifically designed to achieve rigidity and stiffness on impact and also to ensure that there is no ingress of water on the inside of the wedge. The wedge had a rectangular top on which attachments were fitted to vary the mass of the wedge.

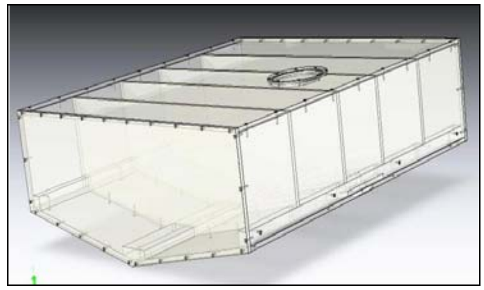

Figure 2. Design of wedge of dead rise angle 10 º (Ref. [5]).

2.2 Instrumentation

A potentiometer cable extension transducer Celesco (PT5MA-150-S47-DN-500) with a range of 150 inches has been used along with two accelerometers (CTC Model AC140-2A) range 50g to measure the instantaneous vertical position and accelerations. The velocity is calculated by a numerical differentiation of the position signal.

Four Piezoelectric pressure transducers (Kistler Model 211B4) were used to measure the pressure on the wedge surface. Their range is 0-200 psi and each of them has diameter of 5.5 mm. They were arranged along the median of transducer attachment on one side of the wedge. Among the four pressure transducers, three of them were close to apex and one was at the corner end of the side.

Two rectangular electromagnets (BRE-4080-110) of size 4" wide x 8" long x 2.5" high each manufactured by Bunting Magnetics Co. have been used so as to achieve remote automatic release of the trolley and wedge. Magnets have a rating of 1000 lbs for lifting application and are powered by 110 volts DC power supply (BPS1-0150-110).

2.3 Release Mechanism

The Electro-magnets were fitted on the top of frame on underside of the cross-bar (Figure 4) and was electrically controlled to trigger the release of the trolley.

2.4 Data acquisition & Sampling Frequency

Data acquisition was carried out using a combination of 8-channel (Differential) data acquisition system DaqBook/2001 (16 bit 200 kHz) Series and an 8-channel expansion card DBK85 (both manufactured by IOtech Inc.) to get 16-differential channels. Preliminary experimental runs have been carried out to verify measurement repeatability and accuracy of the sampling frequency. To check the validity of the chosen sampling frequency, the wellknown Nyquist–Shannon theorem has been applied. The best sampling frequency was found 5 kHz for the drop tests that have been carried out.

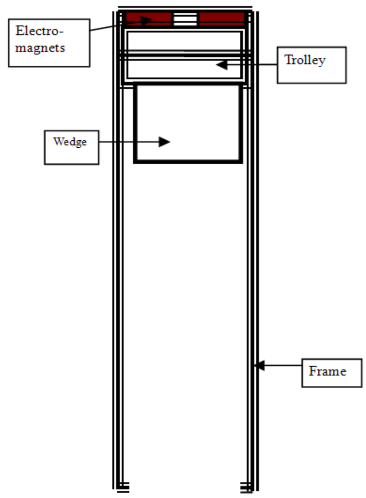

Figure 3. Trolley release mechanism (Ref. [5]).

3. EXPERIMENTAL DATA ANALYSIS

The 10^0 degree deadrise model was dropped from drop heights of 40 cm and 60 cm with additional masses of 20 kg and 40 kg. For each configuration, the trends of the results are similar, that's why only few cases represented here.

Figure 4 shows a typical case of the wedge displacement curve recorded by the position cable transducer. The wedge apex hits the water after a free fall distance of 60 cm with a maximum velocity 3.43 m/s which is much clear in Figure 5.

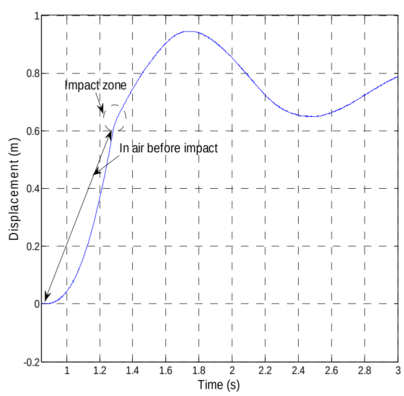

Figure 4. Displacement raw data as a function of time (No extra mass, drop height = 60 cm).

A typical case of the wedge velocity with time identifying the free fall and impact zone is presented in Figure 5. This curve is obtained by filtering the position raw data and using a numerical differentiation. It is evident that the zone of interest where the maximum kinetic energy is lost lasts less than 50 ms following the impact.

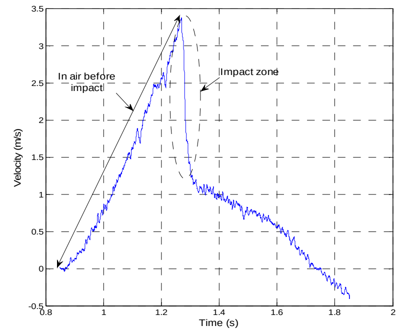

Figure 5. Wedge velocity as a function of time (No extra mass, drop height =60 cm).

Figure 7 shows the spatial pressure distribution at specific times. Each solid line corresponds to a discrete approximation of the spatial pressure distribution at the time of the peak pressure. At t=2.0168s, only one point is shown by circle which corresponds to the spatial pressure distribution at the time of the peak pressure on transducer no.1. In this case the water has reached only the first transducer and the pressure on all the other transducers is very small or close to zero which are not shown in the figure for the sake of clarity. The dotted line joins the peak pressures of all transducers.

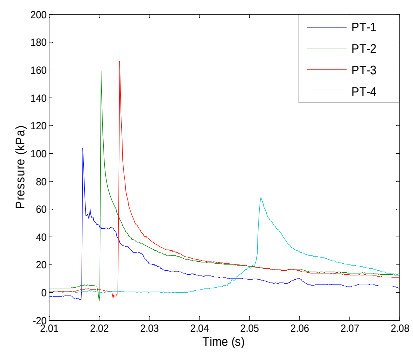

Figure 6. Recorded pressure by four pressure transducers during impact (extra mass=20 kg, drop height =40 cm).

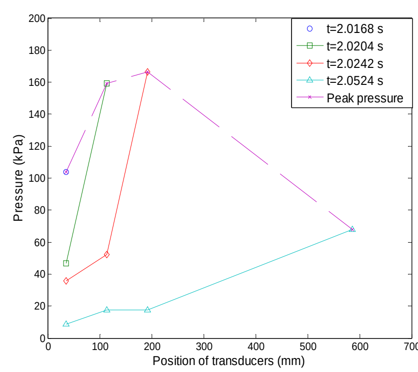

Figure 7. Pressure distribution on the face of the wedge at different times during impact (extra mass=20 kg, drop height =40 cm).

To describe the influence of the parameters on slamming pressure, two non-dimensional quantities have been used:

The entry depth, $\xi = \dfrac{h}{\int v(t)dt}$ (1)

and pressure coefficient, $C_p = \dfrac{p - p_a}{\frac{1}{2}\rho (v(t))^2}$ (2)

where h is the vertical height of a given point on the wetted surface measured from the apex, $v(t)$ is the velocity of the wedge, p_a is the atmospheric pressure which is assumed to zero and ρ is the mass density of water.

Figure 8 shows the influence of the mass of the wedge on pressure coefficient for the 10^0 deadrise model. Three different masses were considered and they were dropped from the same height of 40 cm. The results are plotted for the time when the peak pressure is located at pressure transducer no.3 for all cases. It is evident that the mass of the wedge has negligible influence in predicting maximum pressure coefficient at the maximum dimensionless entry depth, which was also reported by Yettou et al. [14]. The value of the maximum pressure coefficient is found in the order of 80 and is approximately constant, which also matches with the experimental results of Zhao et al. [15] and analytical results of Mei et al. [6].

Figure 9 shows the influence of initial drop heights on pressure coefficient for the 10^0 deadrise model. Two drop heights were considered for the model with an extra mass of 40 kg. The results are also plotted for the time when the peak pressure is located at pressure transducer no.3 for all cases. Same conclusion can be drawn that the maximum pressure coefficient is independent of drop height which was also observed by Yettou et al. [15]. The magnitude of the maximum pressure coefficient is also in the order of 80 as was found by the experimental results of Zhao et al. [15] and analytical results of Mei et al. [6].

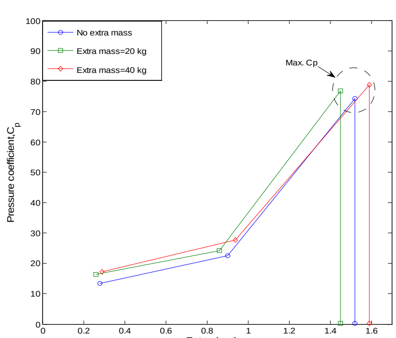

Figure 8. Effect of extra mass on pressure coefficient as a function of dimensionless entry depth at drop height =40 cm.

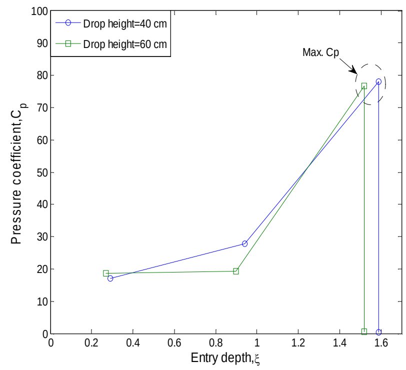

Figure 9. Effect of drop height on pressure coefficient as a function of dimensionless entry depth with extra mass=40 kg

The maximum entry depth for the above cases corresponds to pressure transducer no. 3 which was the last transducer in contact with water at that instant. This maximum entry depth is also found remaining constant in the order of 1.5 as was reported by Yettou et al. [14].

4. COMPARISON WITH CHUANG'S [3] PREDICTION METHOD

S.L. Chuang [3] developed a prediction method for determining slamming pressures of a high speed vessel in waves. This method is based on the Wagner wedge impact theory, the Chuang cone impact theory and NSRDC drop tests of wedges and cones.
According to this method, the pressure acting normal to the hull bottom in the slamming area may be separated into two components [10]:

1. The impact pressure p_i, due to the normal component to wave surface of the relative velocity between the impact surface and the wave.
2. The planing pressure p_p, due to the tangential component to wave surface of the relative velocity between the impact surface and the wave.

The planing pressure is usually small and insignificant compared with the impact pressure. The total pressure due to normal velocity component of the vehicle both normal and tangent to the wave surface is therefore

$$p_t = p_i + p_p \quad (3)$$

In this paper, we only summarized the simplified case of wedge impact pressure in calm water. To estimate the maximum impact pressure, the pressure velocity relation is written as,

$$\text{Max } p_i = k\rho V_n^2 \quad (4)$$

where k is a non-dimensional coefficient, ρ is the mass density of water and V_n is the relative normal velocity of impact body to wave surface.

The relative normal velocity, V_n is determined on the hypothesis that only the velocity component of the moving body normal to the impact surface and the velocity component of the wave normal to its surface generate the impact pressure [10]. For the case of calm water impact, V_n becomes

$$V_n = V_v \cos^2 \beta \qquad (5)$$

where V_v is the vertical impact velocity and β is the deadrise angle.

The non-dimensional coefficient, k is determined as follows,

$$k = k_1 / \cos^4 \beta \qquad (6)$$

The best approximate values of k_1 is expressed by the following equation obtained through the method of curve fitting [10]. For $2.2 \le \xi < 11$ deg:

$$k_1 = 2.1820894 - 0.9451815\xi + 0.2037541\xi^2 - 0.0233896\xi^3 + 0.0013578\xi^4 - 0.00003132\xi^5 \qquad (7)$$

where ξ is the impact angle which is equal to the deadrise angle β in the present case.

For all the cases of drop tests, pressures have been calculated using this method. It has been found that in each case, this method can predict the maximum pressure quite accurate for practical use which is summarized in Table 1.

Figure 10 through Figure 12 show the comparison of recorded pressure with Chuang's [3] prediction method for three cases. It is evident that Chuang's [3] method can predict the maximum pressure almost exactly, provided that the vertical impact velocity is accurate. The main reason of the discrepancy of the results is due to the dynamic noise. Since the velocity is obtained by filtering the raw signal of displacement data and then differentiating them, the vertical impact velocity as an input was not perfectly accurate. This also caused a little bit time delay in predicting the maximum pressure.

Table 1: Comparison of maximum pressure with Chuang's [3] prediction method

Configration	Maximum pressure [kPa] (Experimental result)	Maximum pressure [kPa] (Chuang's [3] method)
No extra mass, 40 cm drop height	151.84	150.49
No extra mass, 60 cm drop height	280.64	268.49
20 kg extra mass, 40 cm drop height	166.51	150.67
20 kg extra mass, 60 cm drop height	262.26	249.41
40 kg extra mass, 40 cm drop height	186.53	171.61
40 kg extra mass, 60 cm drop height	268.64	265.29

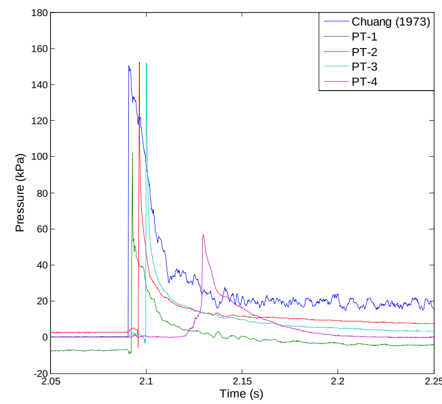

Figure 10. Comparison of recorded pressure with Chuang's [3] prediction method (No extra mass, drop height =40 cm).

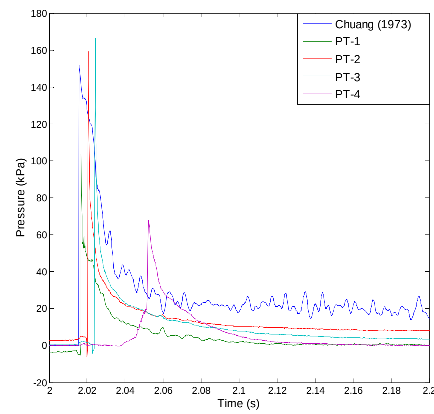

Figure 11. Comparison of recorded pressure with Chuang's [3] prediction method (extra mass=20 kg, drop height 40cm).

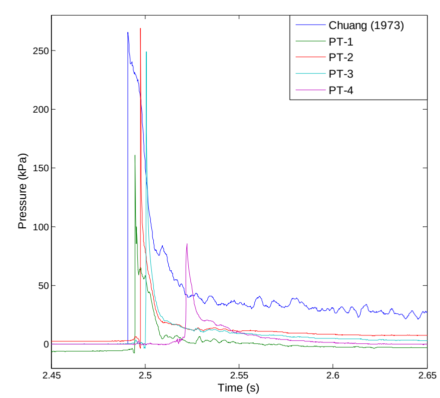

Figure 12. Comparison of recorded pressure with Chuang's [3] prediction method (extra mass=40 kg, drop height =60 cm).

5. CONCLUSIONS

An initial series of free fall drop tests have been performed with the 10^0 deadrise wedge varying the drop heights and the mass of the wedge. For each configuration, the maximum peak pressure was found in either pressure transducer no. 2 or 3, which signifies that the peak pressure tends to increase from keel towards the chine. There was a big gap between pressure transducer no.3 and 4, which should be covered with more pressure transducers in the next experiments to depict the more accurate and complete spatial pressure distribution. The maximum pressure coefficient for this 10^0 model is found approximately constant and in the order of 80 and does not depend on drop heights and mass of the wedge. Chuang's [3] prediction method has been found to predict maximum slamming loads quite accurately for each case, though dynamic noise caused some discrepancies.

Follow up experiments would be performed varying the deadrise of the wedge and changing the deadrise in the same section to account for more actual ship hulls. Some oblique drop tests also need to be performed to get the insight of the slamming phenomenon more accurately. Finally model tests need to be carried out with planing hull in waves to further verify Chuang's [3] method. Then this method would be incorporated in the simulation of planing hull motion.

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