Journal of Subsea and Offshore
-Science and Engineering-, Vol.8

December 30, 2016

Slamming Loads Prediction on a Submarine Hull Structure

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Paper History

Received: 25-September-2016
Received in revised form: 20-December-2016
Accepted: 30-December-2016

ABSTRACT

The paper presents a study of slamming loads prediction on submarine pressure hull through combination results between numerical analysis and a hydro-elastic submarine model test. This prediction of dynamic loads is very useful since the loads may occur when a submarine in an emergency situation has to sail or arise quickly to surface rough sea. The numerical simulation was conducted by applying the linear 2 - D strip theory to obtain response of the submarine motion and relative velocity to sea surface. Based on this numerical results slamming loads were predicted by conducting a fall - test on a submarine hydro-elastic model in the water tank. The amplitude of slamming load obtained from this test compared with the results from the method of Statovy & Chuang for predicting impact pressures. The results of test measurements from the tank test show a good agreement with the impact pressure method.

KEY WORDS: *Submarine, Hydro-Elastic Model, Slamming Loads*

NOMENCLATURE

H_u	Response Function of a Signal u
$U_a(\omega_e)$	Amplitude of Frequency ω_e of Signal u
$\zeta_a(\omega_e)$	Amplitude of Frequency ω_e of Wave Elevation ζ
$S_{uu}(\omega_e)$	Spectral Density of Signal u
$S_{\zeta\zeta}(\omega_e)$	Spectral Density of Wave Elevation ζ
B	Width of mid-ship
b	Half the Width of the Station 0.25L of Bow
L_s	Length of the Ship
L_m	Length of the Model
m_o	The variance of the motion is given by the area under the motion energy spectrum
λ	Geometrical Scale Factor
EI	Bending Stiffness
ω	Wave Frequencies
T	Time
P_i	Impact Pressure
V_n	Normal Velocity Relative of the Hull Ship to the Surface Wave

1.0 INTRODUCTION

Pressure hull which are the main load bearing structures of naval submarines, commercial and research submersibles, and autonomous underwater vehicles (AUVs) whose primary load-bearing responsibility is to withstand hydrostatic pressure associated with diving. However, when the submarine needs to rise to sea surface and sailing in it the static loads may change to dynamic one. These loads can exist due to the structural response of the submarine when hit by waves. The wave impact to the submarine hull can produce secondary or local loads which is called slamming. This phenomenon occurs most often in the rough sea where the high waves sometimes makes the submarine's bow or stern emerge from the water surface and fall back into the waves with a large impact force on the hull and waves on the water surface. Slamming is a transient response resulting from the bow or stern of the ship hull while it is nodding or slamming down. This action generally induces a low frequency, especially in the first mode natural frequency of the hull. The effects of slamming loads on material fatigue damage are quite large. In addition, slamming is always accompanied by whipping where the submarine shudder can interfere with the performance of electronic or mechanical equipment in a submarine during operation.. These events also can cause high load and it is extremely dangerous. The frequency of "whipping" is closely related to the natural frequency of the structure of these submarines. In extreme conditions the submarine structure can suffer severe damage such as cracks or broke into two parts, which had a fatal effect for submarine personnel when performing operations. Figure 1 presented the numerical simulation of slamming occurrence on the submarine.

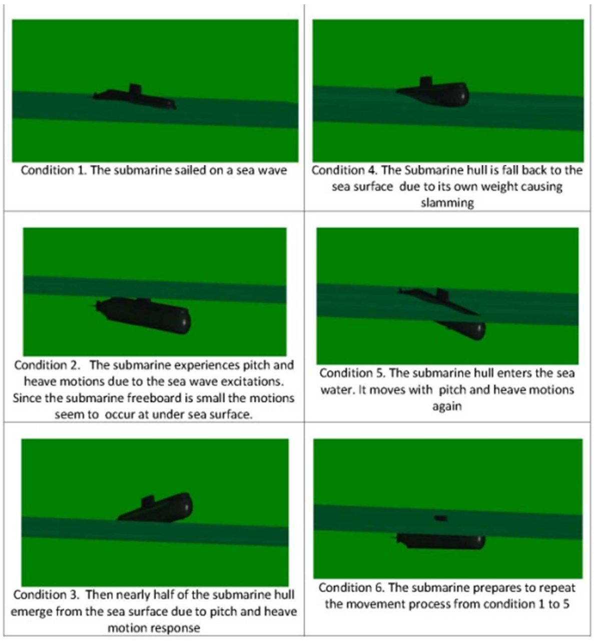

Figure 1: Slamming occurrence on the submarine

To begin this study there was very little information available about a submarine since it belongs to military domain. However, the studied submarine based on type U – 209 basic design where can be found on the internet site en.wikipedia.org [2] and www.heiszwolf.com [1]. The slamming load prediction methods to a surface ship were applied on this study. Many researchers have conducted studies in developing the method of predicting the slamming loads. A comprehensive compilation of the prediction method of slamming analysis technique and procedure has been reported by Ship Structure Committee (SSC-1995). This report contains of an assessment of the state of the art of hydrodynamic impact on the displacement of ship hulls in which these phenomena are still not yet completely understood. Therefore, more design guidance would be extremely useful with the means or methods as to how these phenomena should be avoided from an operational perspective, and/or how their dangerous load effects should properly be repelled or absorbed in the structural design. Since the impact loads of slamming occurs in ~ 1ms, an experimental study of slam stress has proved to be very useful, specifically the model test of containership conducted by J Ramos et al [5] in which a hydro-elastic model was used. One of the conclusions states that the linear strip theory used for the determination of the ship motions agrees in a very satisfactory way with the experimental results for all of the wave frequencies and for the different wave heights. It is also concluded that non-linearity is related to the structural vibration due to the slamming loads and the superposition principle appears to be a reasonable assumption. Timmo kukannen [10] presented a method for wave load predictions for marine structures. His method also considered the non-linearity of the wave loads and the effect on high frequency loads such as slamming. A recent investigation of slamming was conducted by Ahmed A. Swiden [9], where the loads work on the catamaran by applying the finite volume computational fluid dynamics (CFD) method. This method was used to predict the magnitude and peak values of slamming pressure. It was found that the computed pressures far from the initial impact where slam occurs resulted in under predicting slamming pressures. Another methodology for predicting slamming loads are presented by Nugroho WH and AS Mujahid [6]. In their methods slamming loads numerically calculated using combination of 2 – D strip theory for motion prediction and diffraction theory for pressure distribution calculation. The maximum slamming loads then calculated by using ABS rule.

In this paper a combination of numerical approximation and model test results for predicting slamming loads on submarine hull are presented. The numerical approach is to simulate the submarine motions in the sea surface that produce the relative vertical velocity and motion. These relative quantities are then used as a fall – height of the model test to obtain the slam pressure of the submarine.

2.0 SUBMARINE MOTION NUMERICAL SIMULATION

Numerical simulation results as shown in Figure 1, in the introductory part were obtained by using a software-based strip theory to calculate the relative vertical velocity and motion of the submarine. The results were the sea-keeping performance of the submarine which was presented in the value of RAO (Response Amplitude operators). RAO or Response function value is the ratio between the spectral density of motion or velocity and wave relative to each encounter wave frequencies [4]. The RAO for the displacement can be calculated according to the following equation :

$$RAO_{u_a}(\omega_e) = \frac{u_a(\omega_e)}{\zeta_a(\omega_e)} = \sqrt{\frac{S_{uu}(\omega_e)}{S_{\zeta\zeta}(\omega_e)}} \qquad (1)$$

where :

RAO_{u_a} = response amplitude operators of a signal u_a
u_a (ωe) = amplitude of frequency ωe of signal u
ζ_a (ωe) = amplitude of frequency ωe of wave elevation ζ
S_{uu} (ωe) = spectral density of signal u
$S_{\zeta\zeta}$ (ω_e) = spectral density of wave elevation ζ .

For velocity – RAO the following equation can be used:

$$H_{\dot{u}} = \frac{\dot{u}_a(\omega_e)}{\zeta_a(\omega_e)} = \omega_e \sqrt{\frac{S_{uu}(\omega_e)}{S_{\zeta\zeta}(\omega_e)}} \tag{2}$$

where :

$RAO_{\dot{u}_a}$ = response amplitude operators of a signal $\dot{u}_a$

$\dot{u}_a(\omega_e)$ = amplitude of frequency ω_e of signal $\dot{u}_a$

From the calculation above statistically RAO of relative velocity and motion from the surface of the sea surface on each desired location of the submarine will be obtained. Theoretically when the submarine experiences slamming it must have two conditions [4] firstly the bow emerged from the sea surface relative vertical motion must be greater than draft in the bow. Secondly, the relative velocity at the bow on the sea surface at the time of impact must be greater than threshold velocity (u*). This threshold velocity is calculated based on experiments with various forms of the ship which can be written as follows:

$$u^* = \frac{0.0195B}{b}\sqrt{Lg} \tag{3}$$

Where B is the overall width of the mid-ship; b is half the width of the station 0.25L from the bow, with the position of 0.03B above the keel; and L is the length of the ship. Lines plan of the submarines that used on this study is type U - 209 and has a principal dimension of LPP = 61.26 m, BOA = 6,2m, HOA = 11.65 m and T = 5.5 m. The lines plan is presented in Figure 2. The numerical simulations performed in order to obtain the response amplitude operator (RAO) relative vertical motion and velocity of the submarine at a certain position is shown in Figure 3. For convenience in analyzing, the submarine is divided into ten (10) stations. The prediction location is determined by assuming that this place is prone to dynamic loads which will affect the performance of submarine. The locations are a quarter length of LPP from the bow where the torpedo storage area is built, and around mid-ship section where the control room and periscope are operated then at a quarter length of LPP from the stern where the main engine of a submarine is located.

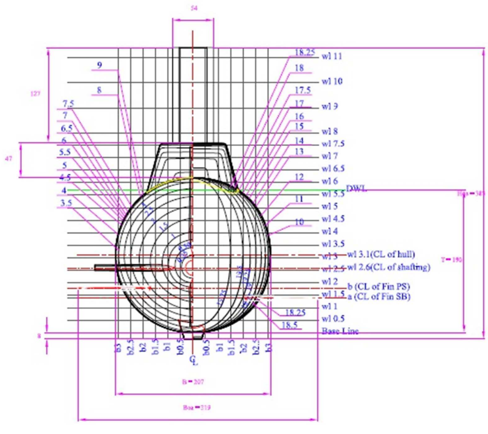

Figure 2: Body Plan of submarine type U-209.

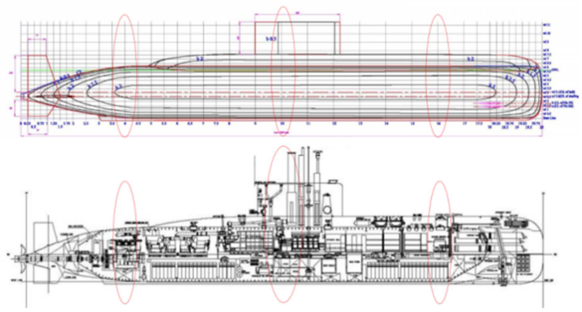

Figure 3: The location of slamming load prediction.

In this simulation the submarine operated in surface of sea water with environmental conditions according to JONSWAP formula with Hs = 5 m Tp = 13.772 seconds or sea state 6 [9]. The spectral density wave is shown at Figure 4. RAO relative vertical motion and velocity calculation results are presented in Figures 5 and 6. These RAO results show a peak at which the maximum response of relative vertical motion or velocity occurred. From these figures RAO value for the relative vertical motion and velocity is the highest in the area of the bow and the lowest in the ST 01. The reason for this is that the wave is in head sea direction. Also, it can be understood that the stern area may experience high relative vertical motion and lead to slamming although it may not as high as the bow area. The significant relative vertical motion and velocity as results of the statistical analysis are tabulated in Table 1 From this table it can be seen that the submarine may experience slamming.

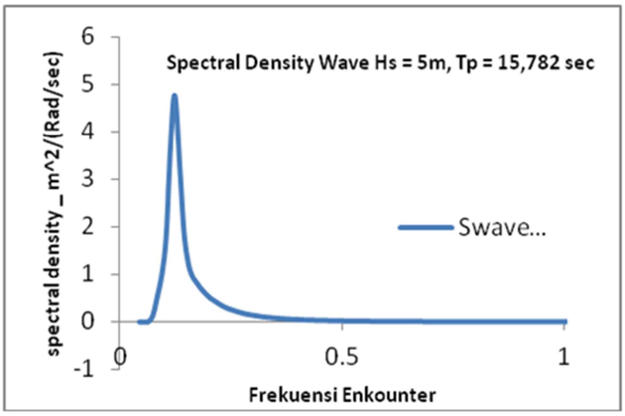

Figure 4: Spectral density of wave Hs = 5m, Tp = 13, 782 s

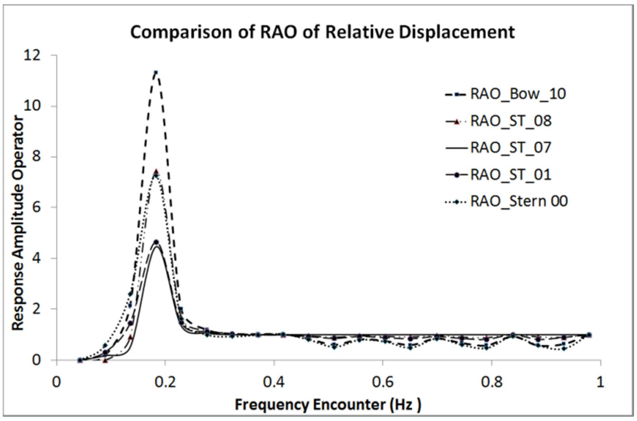

Figure 5: Comparison of RAO of Relative Displacement

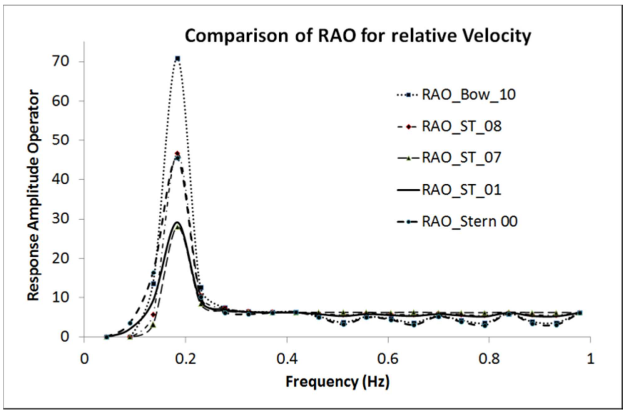

Figure 6: Comparison of RAO of Relative Velocity

Table 1: The significant relative vertical motion and velocity

	m_o	Units	RMS motion	Units	The significant motion amplitude	Units
ST7_04: Rel. vert. velocity	8.258	m^2/s^2	2.874	m/s	5.747	m/s
ST1_04: Rel. vert. velocity	11.663	m^2/s^2	3.415	m/s	6.83	m/s
ST8_04: Rel. vert. velocity	21.641	m^2/s^2	4.652	m/s	9.304	m/s
ST7_04: Rel. vert. motion	4.889	m^2	2.211	m	4.422	m
ST1_04: Rel. vert. motion	7.86	m^2	2.803	m	5.607	m
STERN_00: Rel. vert. velocity	27.994	m^2/s^2	5.291	m/s	10.582	m/s
ST8_04: Rel. vert. motion	15.416	m^2	3.926	m	7.853	m
STERN_00: Rel. vert. motion	21.667	m^2	4.655	m	9.31	m
Bow0: Rel. vert. velocity	54.75	m^2/s^2	7.399	m/s	14.799	m/s
Bow0: Rel. vert. motion	42.352	m^2	6.508	m	13.016	m

3.0 FALLING - TEST OF A SUBMARINE MODEL

A slamming load is non-linear and transient in which it contributes greatly to a fatigue of structure. To obtain this phenomenon it is necessary to test using submarine hydro-elastic models where the elastic properties of material structures of the submarine also modeled. Ideally for slamming loads measurement is conducted when the submarine is in a water wave, but because the wave generation facilities of the tank does not work well so the hydrodynamic loads are simulated by performing a "fall test". This test was conducted by free – fall the submarine model into the tank in a particular elevation. Then the impact loads that occur on the submarine hull model were measured.

As seen in Figure 7, a hydro - elastic model scale 1: 30 was manufactured. This submarine model has a steel-bar backbone located in the keel which has flexural stiffness similar to the full scale submarine (see Table 2). The arrays of accelerometer were placed on top of the steel back bone (see Figure 8) to detect changes in acceleration due to changes of load. The accelerometer positions were at a quarter length of LOA from the bow (ST 16), mid-ship (ST 10) and at a quarter of LOA from the stern ship (ST 04) where presumably the slamming and highest loads may occur. The hydrodynamic load impact due to slamming in this study was obtained by measuring the acceleration that occurs on the model submarine when it hits the surface of the water. The acceleration data were collected with sampling rate of 1000Hz, to have the transient response of the load [7].

Figure 7: Installment of back-bone steel bar on the keel as submarine pressure hull elastic model

Figure 8: Accelerometer placement on Submarine Model

Table 2: Properties of Submarine hydro- elastic model

Physical property	Units
EA/L (stiffness of backbone steel)	**108.9 MN/m**
LOA (length over all)	**2.04 m**
Breadth	**0.206 m**
Draught	**0.190 m**
Displacement	**55.45 kg**

The test procedure is shown in Figure 9 to Figure 12. Figure 9 shows the preparation of "fall test" where the submarine model suspended by a cable in a particular elevation. Then this hydro-elastic submarine model was released from a cable using a "release mechanism" that shown in Figure 10. Then, in Figure 11 shows the submarine model hit the water surface. And, finally the submarine model was back into her surface draft position which is shown in Figure 12.

Variations of the water surface elevation based on the results of numerical calculation theory strip in form of vertical motion and velocity relative to the sea surface when the slamming experienced by the submarine. The vertical motion data was scaled down to obtain the fall - height on the water tank. The relative velocities were needed to convert to elevation data using the fall free gravitational law before they were scaled down to the water tank condition. The fall height data of submarine model is shown in Table 3.

The response of fall loads of the hydro-elastic submarine model measured by accelerometers that installed on the selected position of the model.

Table 3: Fall Height Data of Submarine Model

	The significant motion amplitude	Units	Using Free fall gravity law Change to Height (m)	Model Scale (cm)
ST7_04: Rel. vert. velocity	5.747	m/s	1.683	5.611
ST1_04: Rel. vert. velocity	6.83	m/s	2.377	7.925
ST8_04: Rel. vert. velocity	9.304	m/s	4.412	14.705
ST7_04: Rel. vert. motion	4.422	m	4.422	14.740
ST1_04: Rel. vert. motion	5.607	m	5.607	18.690
STERN_00 : Rel. vert. velocity	10.582	m/s	5.707	19.023
ST8_04: Rel. vert. motion	7.853	m	7.853	26.177
STERN_00 : Rel. vert. motion	9.31	m	9.31	31.033
Bow0: Rel. vert. velocity	14.799	m/s	11.161	37.205
Bow0: Rel. vert. motion	13.016	m	13.06	43.387

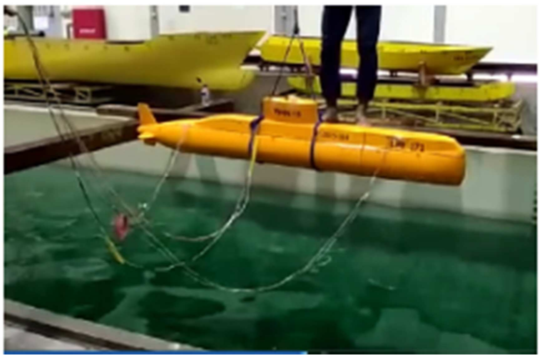

Figure 9: A submarine hydro-elastic model suspended by a cable

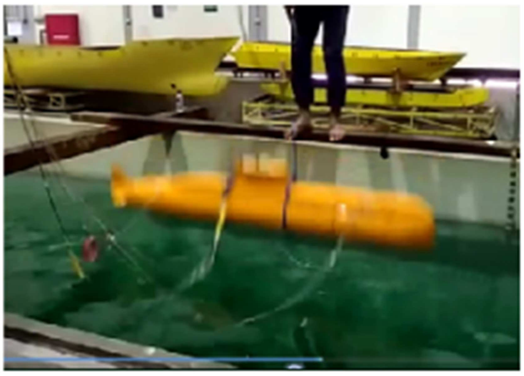

Figure 10: The submarine model was released from cable using a “release mechanism”.

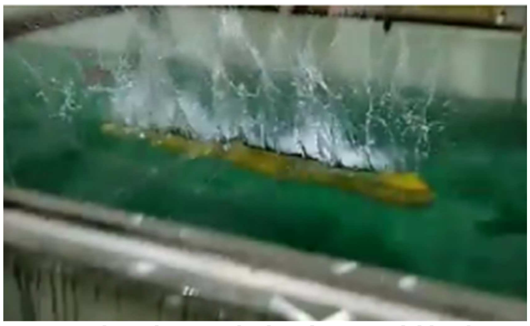

Figure 11: The Submarine hydro-elastic model hit the water

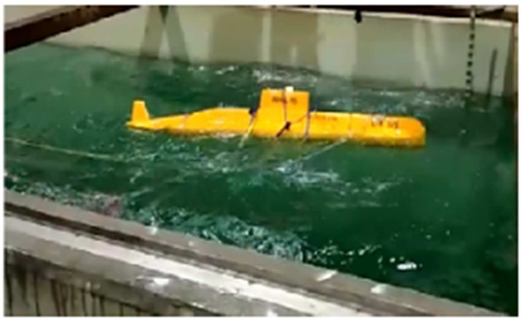

Figure 12: Submarine hydro- elastic model was on her surface draft

4.0 RESULT ANALYSIS AND DISCUSSION

This section discusses the analysis of the test results. An example of measurement results from the fall test accelerometer is shown in Figure 13. The highest amplitude on this figure is assumed to be the peak of the accelerometer signal when the submarine hit the water surface at the water tank. The results of data processing for all heights in the third position (ST 4; ST 10; ST 16) are shown in Table 4. These results indicate that the impact pressure is getting higher due to the increasing relative height from the water surface.

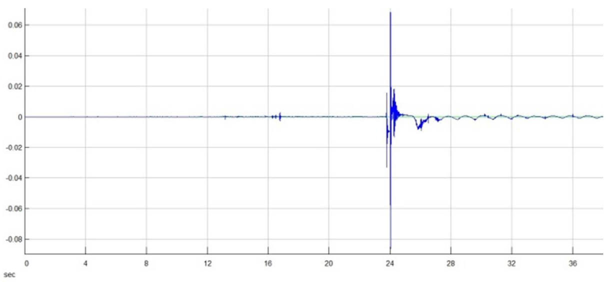

Figure 13: Examples of measurement result of fall - test

Table 4: Fall test - Measurement Result of impact pressure

	H Full Scale (m)	Fall Test (Mpa)
ST4	2.378	3.523
ST10	1.683	2.524
ST16	4.412	6.451
ST4	4.422	6.465
ST10	5.607	8.170
ST16	7.853	11.402

The impact pressure of fall - test results from this study are compared with Stavovy and Chuang [3], where their methods provide a procedure to compute slamming impact pressure of high performance vehicles (HPV). They provided an empirical formula based on two- and three-dimensional data. The method determines the impact pressure in an infinitesimal area of the hull bottom. In that area the dead rise, buttock trim and heel angles are determined from ship lines, body plan, ship motions and wave profile.

The empirical formula for impact pressure is shown as follows:

$$p_i = k_1 V_n^2 \tag{4}$$

Where,

P_i = Impact Pressure (Psi)
V_n = normal velocity relative of the hull ship to the surface wave (ft/s)

Values for k_1 shown in Figure 14 as a dotted line.

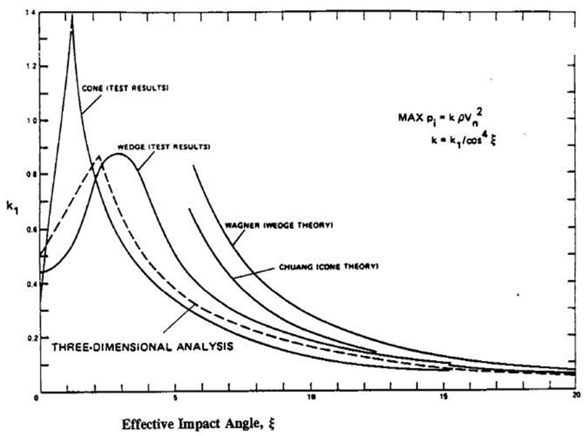

Figure 14: Values for k_1 of Stavovy and Chuang method (SSC-385.1995)

The normal relative velocity as input data for Chuang – Stavovy method is obtained from Table 3. However, the relative vertical motion from the numerical simulation has to be converted to the height data by applying the free – fall law of gravity. The results of this method show in Table 5.

Table 5: Impact pressure of Chuang - Stavovy method.

Items	Vn Relative (m/s)	k(3-D factor based on body plan)	Impact Pressure (MPa)
ST4	6.83	0.8	2.777
ST10	5.747	0.7	1.716
ST16	9.304	0.83	5.333
ST4	9.314	0.83	5.345
ST10	10.489	0.7	5.716
ST16	12.413	0.8	9.149

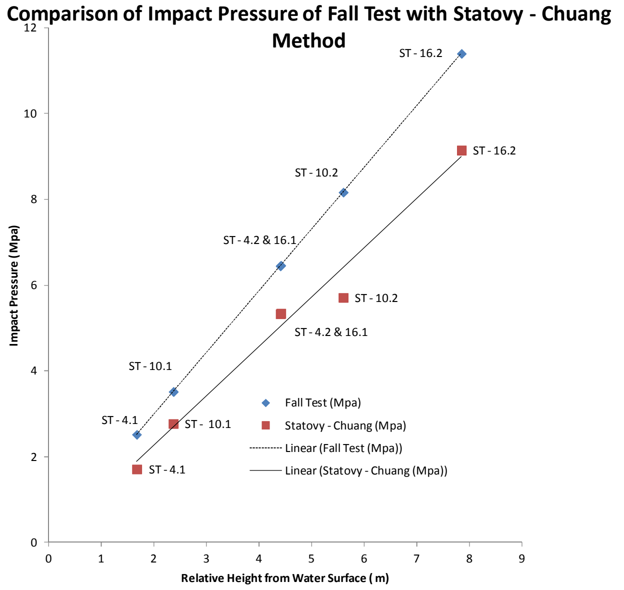

Figure 15: Comparison of Amplitude slamming test result falls vs methods Statovy - Chuang on the body of submarine.

The comparison results of slamming amplitude between fall test and statovy – chuang method is shown in Figure 15. From this picture shows the pattern produced by these two methods are similar, but tend to fall - test has a higher impact value. The difference value impact pressure generated by these two methods ranges from 30%. This is probably because the value of k_1 in Statovy and Chuang are more likely to applications in the form of the surface hull and numerical methods. This actually supported also by the Figure 15 where the value k_1 of the wedge test tend to be larger than other numerical approximation.

5.0 CONCLUSION

This study has been successfully presented a method for predicting slamming pressure on a submarine- hull for design purposes. The comparison to a well-known Stavovy and Chuang method has been made to validate this method of study and found that the results agree well each other. Finally, this method of calculation can be used as an alternative slamming load determination for approximation the strength, lifetime and size of the submarine structural components.

ACKNOWLEDGEMENTS

The authors highly appreciated a research grant from the Ministry of Research and Technology and Higher Education Republic of Indonesia through INSINAS RT – 2015 - 108 and INSINAS RT-2016 - 314 research program to conduct this study.

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