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Hydrodynamic Modeling of Water-Entry of the Wedge Shape with Considering Asymmetric Impact

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ABSTRACT

The slamming of the planing crafts is the most important structural phenomenon that a vessel is encountered during their career. Many researchers have investigated this phenomenon in various methods. In this paper we investigated the analytical results of impact of symmetrical wedge to the water surface briefly, then the asymmetric impact of a 2D section of a wedge to the water surface was studied. To analyze above phenomenon, we used a numbers of analytical relationships that summarizes how to achieve these equations. Finally, obtained analytical relationships were used to determine the pressure distribution and maximum value on a wedge with different deadrise angles. The results indicated good agreement between the obtained results and results of other researcher's studies.

KEYWORDS: *Analytical Method, Asymmetric Impact, Wedge, Pressure Distribution.*

NOMENCLATURE

ρ	Water density
c	Instantaneous half beam of the section
$\dot{c}$	Time derivative of c
d	Depth of penetration
β	Deadrise angle
W	Normal velocity
M_{zz}	Added mass
t	Time

1.0 INTRODUCTION

In high speed craft one of the most important forces acting on the structure is the slamming force of impacting to the water surface. Slamming is doubly important for designers, first, analysis of dynamic behavior of vessel, because this phenomenon, by creating strong forces in front of vessel causes negative acceleration on the ship movement, and it affects strongly on the movement of vessel. Second, forces arising from this phenomenon, because these forces are one of the most important external forces on planing hull body.

This force cause's severe local damage to the front of vessel and in extreme conditions, buckling intermediate deck is not unexpected. It should be noted that the force of the slamming, increases with increasing speed.

Hua, [1] discovered the importance of this issue when specifying the difficulty of evaluating the design loads for planing craft with the Theoretical methods.

Rose& Rutersson, [2] while measuring the hydrodynamic pressure by using a real size model boat in wave condition, came to this topic that the front waves have more pressure than surface waves because of asymmetric condition. This issue has been analyzed so far with the help of numerical methods, similarity solution and experimentally data.

For the first time T. von Karman [3] studied the issue of impact of wedge to surface of water, with momentum theory. In this theory the rise of level of water and the effect of gravity is negligible.

In 1932 H. Wagner [4] began new research in this field. In his own research, he considered rise up level of water.

In Wagner method, for small angles of uplift and assuming no trapped air, better values for hydrodynamic force and maximum pressure was obtained. In this way, at the point of impact of free surface to the body, singularities were seen.

Many researchers have done several activities according to Wagner's theory.

Watanabe [5] in1986, eliminated singularities by matching Flow solution of the body in zone root spray with Wagner solution in the outside zone. However solution of inside area was not high degree of accuracy.Armand and Cointe [6] in 1987 eliminated singularities by coinciding the results of Wagner method in both inside and outside zone.Howison, [7] in 1991, developed Armand and Cointe methods in order to meet a wider range of body.

Cointe [8] in 1991, used Howison method, for two kinds of wedge with both small and large deadrise angle.Faltinsen, [9] in 2002 considered various inside and outside areas than Wagner methods.In this paper, to calculate the asymmetric pressure distribution of impact, a simple method is set according Wagner generalized method and this theory was provided by Toyama [10].

The provided formula in this paper is followed by the method that Wagner used for wedge that is entering the water in symmetric mode. One of the assumptions used to provide how to distribute the pressure caused by impact on the wedge, is the profiles shape on water in the area of impact, that this figure is based on the Wagner's impact theory. Although this method derived from a simple perspective, its results compared with a more complex numerical method that is derived from Scolan, [11] are acceptable. Wang [12] understood the importance of effect of asymmetric body shape of planing craft while entering water surface.in addition, many laboratory activities have been done in this field

2.0 IMPACT OF WEDGE TO THE SURFACE

Wagner in 1932 investigated impact of wedge to the water surface and by assuming the ideal fluid, obtained the added mass that is caused by the impact of asymmetric wedge entering water with constant speed and specific weight. Finally by gaining speed fluid rising up around the body and integration of it, Wagner obtained height of rising up fluid in specific distance from the axis [13].

Toyamain 1993 [14], studied about the wedge entrance to water with specific mass and constant speed in asymmetric mode. For this purpose, he used the linear model of body that had been used in Wagner model. Toyama by assuming that fluid is ideal and by defining a parameter that determines the asymmetrical section, calculated the fluid rise up speed around the body and by integrating on the equation, water rise up level obtained. Finally, with regard to the assumption of linearity of the body and the potential equation of a flat plate, pressure distribution due to impacting on water was obtained and therefore points with maximum pressure was specified. In this paper we studied about Toyama modeling and the results of his work.

2.1Wagner's theory for symmetric impact

Wagner investigated the fluid flow around a wedge with mass per unit length (m) that is entering the water at a constant speed. His work was based on von Karman original idea, so during the impact phenomenon, the momentum of the falling wedge transfers to water. Body momentum, when it impacts the water level, is m.v_0, while m is the mass of the wedge and v_0 is velocity of the wedge at the moment of impact. During the water entry, wedge speed will be reduced and its mass increases due to the inertia of the surrounding water. This apparent mass is called the added mass (M_{zz}).

Considering the presence of external forces such as gravity, buoyancy and friction forces, themomentum equation becomes

$$M\dot{V} + \frac{d}{dt}(M_{zz}V) = F \tag{1}$$

As can be seen slamming force directly depends on added mass and its changes in time. By assuming the ideal fluid, we can conclude that fluid movement in length will be non-rotation and there will be a potential speed φ. When continuity equation is valid, added mass is calculated by following equation:

$$M_{zz} = \frac{P}{V^2}\iint \phi \frac{\partial\phi}{\partial\eta} ds \tag{2}$$

Where η is the entrance of the wedge into the water. Wagner solved Laplace equation by taking into account the two boundary conditions on the planing craft and free surface.He gained vertical velocity of the fluid around the body. Figure 1 shows the Wagner assumptions for symmetrical wedgeto the surface of water.

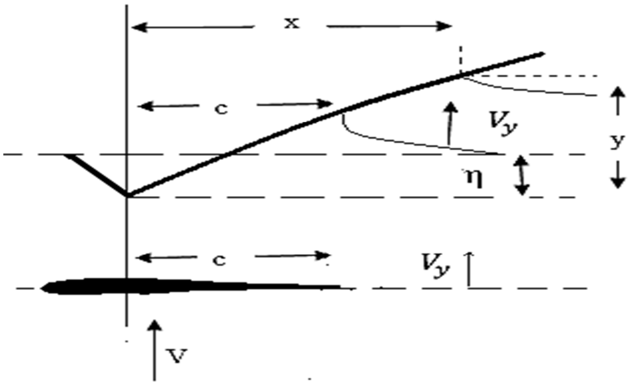

Figure1. Wagner assumptions for symmetrical wedgeto the surface of water

According to initial assumptions in figure (1), the vertical velocity of the fluid at point x from the center of the wedge is calculated by equation (3).

$$V_y = \frac{v}{\sqrt{1 - \frac{c^2}{x^2}}} \tag{3}$$

By integrating of this equation, the water rise up level will be calculated. For four conditions, linear, second-order, third-order and fourth-order of section shape, Wagner calculated level of rise up of wateras shown in Figure 2.

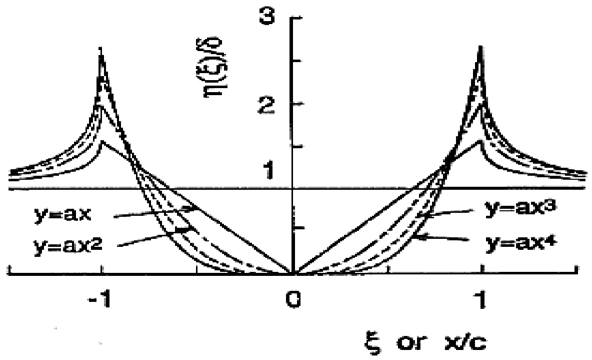

Figure 2: Entering sections with different forms into water [15]

2.2 Toyama Modeling of the asymmetric impact of wedge to the water surface

In this section to obtain analytical solution for computing distributed pressure on the planing craft hull with chine section, by taking advantage of Wagner potential theory and developing it for 2D impacting to the surface, we will study the asymmetric impact. To transfer the result to 3D and to obtain lift, roll forces and momentum of trim and yaw ,we will use the theory of slender body.

Toyama by assuming ideal fluid and by defining a parameter which characterizes the asymmetry of the section, obtained the speed of fluid rising up around the body and with the integrating of the equation, also obtained water rising up level. Finally, considering the assumption of linear body and potential equation on a flat plate, pressure distribution due to impact on the water and therefore the points with maximum pressure is obtained. In this section we will discuss about Toyama modeling and the results of his works. Entry wedge into the water diagram in asymmetric mode are shownbelow [16].

Figure 3 shows the asymmetric impact of wedge to the surface of water so that the $\beta_2$and β_1 are deadrise angle andC_1 , C_2 are half wetted beam, on both sides of the body. For asymmetric impact, average half wetted beam and its variations, can be considered as follows:

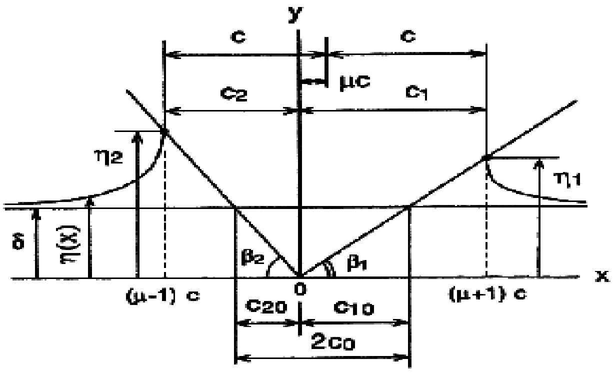

Figure 3: Assumption and parameter of Toyama in asymmetric impact [16].

$$c = \frac{1}{2}c_1 + \frac{1}{2}c_2 \qquad (4)$$

$$\dot{c} = \frac{1}{2}\dot{c}_1 + \frac{1}{2}\dot{c}_2 \qquad (5)$$

As shown in figure (3), (μ) parameter determines the rate of asymmetric impact so that if μ=0, it will be the same Wagner primary mode.

Toyama by assuming the ideal fluid and constancy of the speed of the entry of wedge into the water, calculated the spray water speed around the planing craft body in the form of equation (6).

$$v_y(x) = V/\{1 - \left[\frac{c}{x - \mu c}\right]^2\}^{1/2} \qquad (6)$$

As can be seen by letting μ=0(symmetric mode) we get to the equation that was presented by Wagner. Now, with the integrating of this equation, the position of water around the planing craft anywhere with the distance x from wedge axis can be achieved.

$$\eta(x) = \int_0^t v_y\,(x)dt \qquad (7)$$

By modifying the appropriate variable, the above integral can be simplified as follows:

$$\bar{\eta}(\mu,\xi) = \delta\int_0^1 |\xi - \mu\eta|\{\xi^2 - 2\mu\xi + (\mu^2 - 1)\eta^2\}^{-\frac{1}{2}}d\eta \qquad (8)$$

So that:

$$\mathrm{V}c/_{\mathrm{v}} = \delta,\quad x = \xi,\qquad u = \eta$$

We can change equation (8) such as follows:

$$\bar{\eta}(\mu,\xi) = \begin{cases}\xi A_1 - \mu A_2, \xi > \mu + 1\\ -\xi A_1 - \mu A_2, < \mu + 1\end{cases} \qquad (9)$$

Where the coefficientsA_1 and $A_2$are calculated as follows:

$$A_1 = \frac{1}{\sqrt{1-\mu^2}}[\sin^{-1}\frac{1-\mu^2+\mu\xi}{|\xi|}] \qquad (10)$$

$$A_2 = \frac{1}{1-\mu^2}[|\xi|(\xi^2 - 2\mu\xi + \mu^2 - 1)^{\frac{1}{2}} - \mu\xi A_1 \qquad (11)$$

And for lift up water (ξ=μ±1) on both side of craft, we have:

$$\frac{\eta_1}{\delta} = \frac{\frac{\pi}{2} - \sin^{-1}\mu - \mu\sqrt{1-\mu^2}}{\{(1-\mu)\sqrt{1-\mu^2}\}} \qquad (12)$$

$$\frac{\eta_2}{\delta} = \frac{\frac{\pi}{2} + \sin^{-1}\mu + \mu\sqrt{1-\mu^2}}{\{(1+\mu)\sqrt{1-\mu^2}\}} \qquad (13)$$

On the other hand, according to the figure (3) $\eta_1$and $\eta_2$can be expressed as follows:

$$\eta_1 = (1+\mu)c\tan\beta_1 \tag{14}$$

$$\eta_2 = (1-\mu)c\tan\beta_2 \tag{15}$$

Substituting values of equation (14) and (15) into equations (12) and (13) and considering $R=\frac{\tan\beta_2}{\tan\beta_1}$ results in (16):

$$\sin^{-1}\mu + \mu\sqrt{1-\mu^2} = \frac{\left(\frac{\pi}{2}\right)(R-1)}{R+1} \tag{16}$$

The asymmetry parameter can be obtained from the anglesβ_1 and β_2 in the above equation.However, because the asymmetry parameter μ is always smaller than 1, and in most cases is much smaller than 1 in (|μ|≤1), the above equation (16) can be simplified as:

$$\mu=\left(\frac{\pi}{4}\right)\frac{(R-1)}{(R+1)} \tag{17}$$

In order to find μ, Toyama presented following empirical equations that is approximate solution of equation (12). [17]

$$\begin{cases} f(x).\dfrac{R-1}{R+1}, R\geq 1 \\ f\left(\dfrac{1}{R}\right).\dfrac{R-1}{R+1}, R<1 \end{cases} \tag{18}$$

$$f(R)=\begin{cases} 0.77+0.003R+0.0016R^2, & 1\leq R<3 \\ 0.76+0.015R-0.0005R2, & 3\leq R<10 \\ 0.80+0.0072R-0.00013R2, & 10\leq R<20 \end{cases}$$

2.3. Modified Modeling of the asymmetric impact of wedge to the water surface

Figure 4 shows a wedge section with asymmetry entry whereβ_1 ,β_2,c_1 *and* c_2 are the deadrise angle and the half beam in side 1 and 2 respectively.

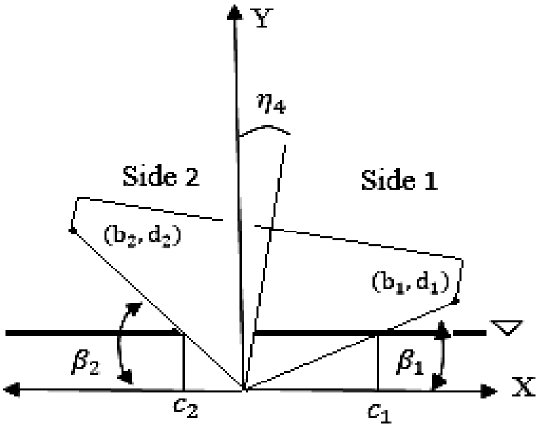

Figure 4: Tascón assumptions in asymmetric impact

Toyama (1993) introduced μ as asymmetric parameter but in the current model this parameter is evaluated as [15]:

$$\mu=\frac{1}{2}(c_1-c_2) \tag{19}$$

$$\dot{\mu}=\frac{1}{2}(\dot{c}_1-\dot{c}_2) \tag{20}$$

Proposed potential function for the asymmetric impact is as follows:

$$\varphi=w\sqrt{c^2-(-\mu+x)^2} \tag{21}$$

The potential functionwas derived respect to time and space, and substituted in energy equation, was obtained the pressure distribution for the asymmetric entry in the follow way:

$$\frac{p}{\rho} = -\dot{w}\sqrt{c^2-(-\mu+y)^2} + \frac{w(c\dot{c}+(-\mu+y)\dot{\mu})}{\sqrt{c^2-(-\mu+y)^2}} - \frac{w^2}{2}\frac{(-\mu+y)^2}{c^2-(-\mu+y)^2} \tag{22}$$

For a wedge sectionis assuming that the asymmetric does not affect the jet velocity, half wetted beam and its variation, in the case of dry chine, can be calculated from (23) and (24):

$$C=\frac{\pi}{4}wt\left(\frac{1}{\tan\beta_1}+\frac{1}{\tan\beta_2}\right) \tag{23}$$

$$\dot{C}=\frac{\pi}{4}w\left(\frac{1}{\tan\beta_1}+\frac{1}{\tan\beta_2}\right) \tag{24}$$

The asymmetry parameter and its variation is calculated as:

$$\mu=\frac{\pi}{4}wt\left(\frac{1}{\tan\beta_1}-\frac{1}{\tan\beta_2}\right) \tag{25}$$

$$\dot{\mu}=\frac{\pi}{4}w\left(\frac{1}{\tan\beta_1}-\frac{1}{\tan\beta_2}\right) \tag{26}$$

While w is downward vertical velocity in direction of axis Y, and t is entering time of wedge to the water surface.

The above equations are for dry chine mode. In wetted chine mode, half wetted beam is calculated as follows. In the case of wetted chine in the side 1, the boundary condition is P=0 in $y=b_1$.

The pressure on the side 1 (right side) can be determined by the following equation:

$$\frac{P}{\rho} = \frac{w(c\dot{c}+(-\mu+b_1)\dot{\mu})}{\sqrt{c^2-(-\mu+b_1)^2}} - \frac{w^2}{2}\frac{(-\mu+b_1)^2}{c^2-(-\mu+b_1)^2} = 0 \tag{27}$$

By simplifying the equation (27):

On the other hand, from the previous equations can be concluded

$$\frac{2}{3}\frac{[C^2-(-\mu+b_1)^2]^{\frac{3}{2}}}{(-\mu+b_1)^2} - 2\sqrt{C^2-(-\mu+b_1)^2} + 2C\ln\left|\frac{C+\sqrt{C^2-(-\mu+b_1)^2}}{(-\mu+b_1)}\right| = w(t-t_1) \tag{28}$$

where t_1 the instant is when the chine wetting from the side 1 occurs. On other hand from the equation (4), (5), (19) and (20):

$$c_2 + \mu = c \quad (29)$$

$$\dot{c}_2 + \dot{\mu} = \dot{c} \quad (30)$$

Assuming that the wetted chine in the side 1 does not affect the half wetted beam in the side 2:

$$c_2 = \frac{\pi}{2}\frac{wt}{\tan\beta_2} \quad (31)$$

$$\dot{c}_2 = \frac{\pi}{2}\frac{w}{\tan\beta_2} \quad (32)$$

The equations (28), (29), (30) were solved iteratively to calculate c and μ. The equations (27), (30) and (32) were resolved to obtain $\dot{c}$ and $\dot{\mu}$. By substituting the result in equation (22), the pressure distribution on wedge was obtained. When occurs the chine wetting in side 2, the boundary condition become: P=0 in y=b_2 and finally, the pressure on the side 2 (left side) can be determined by the following equation:

$$\frac{P}{\rho} = \frac{w(c\dot{c} + (-\mu + b_2)\dot{\mu})}{\sqrt{c^2 - (-\mu + b_2)^2}} - \frac{w^2}{2}\frac{(-\mu + b_2)^2}{c^2 - (-\mu + b_2)^2} = 0 \quad (33)$$

By simplifying equation (33):

$$\frac{2(c\dot{c} + (-\mu + b_2)\dot{\mu})\sqrt{c^2 - (-\mu + b_2)^2}}{(-\mu + b_2)^2} = w \quad (34)$$

By integrating theequation (34):

$$\frac{2}{3}\frac{[C^2 - (-\mu + b_1)^2]^{\frac{3}{2}}}{(-\mu + b_1)^2} - 2\sqrt{C^2 - (-\mu + b_1)^2} + 2C\ln\left|\frac{C + \sqrt{C^2 - (-\mu + b_1)^2}}{(-\mu + b_1)}\right| = w(t - t_1) \quad (35)$$

Where t_2 is the instant when the chine wetting from the side 2 occurs.When chine wetting occurs in both sides, the equations (28) and (35) are solving to calculate c and μ, and $\dot{c}$ and $\dot{\mu}$ are obtained resolving (34) and (27). Then, with substituting the values in equation (22), pressure distribution obtained. Also by using the same equation, pressure distribution in different heel angles is obtained.

3.0 RESULTS

The Figures 5~8 show the results of pressure distribution on wedge section for deadrise angles of $\beta_1 = 10$ and $\beta_2 = 30$.
The dimensionless coefficient of pressure is calculated as:

$$C_p = \frac{P}{\frac{1}{2}\rho w^2} \quad (36)$$

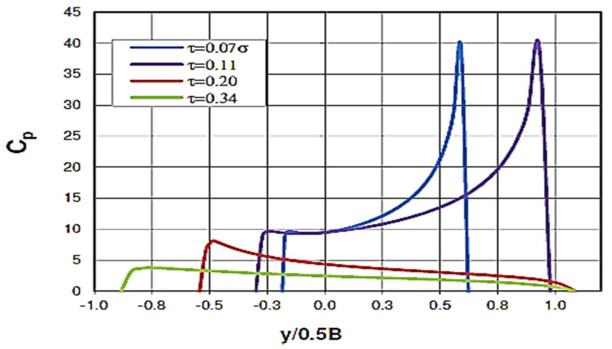

Figure 5: Pressure distribution for $\beta_1 = 10$ and $\beta_2 = 30$

The results show that in the first wedge impact to the surface, the water pressure on the right side suddenly rises. But when chine was wet in the same side, the pressure on the right side, reduced and on the left side increased. Figures 5 and 6 show the pressure distribution before chine wetting in the side 1. The results are compared with Toyama (1993) and CFD modeling [18, 19].

Figures 7 and 8 show the pressure distribution before and after chine wetting in the side 2 respectively. The results data are compared with CFD simulations.

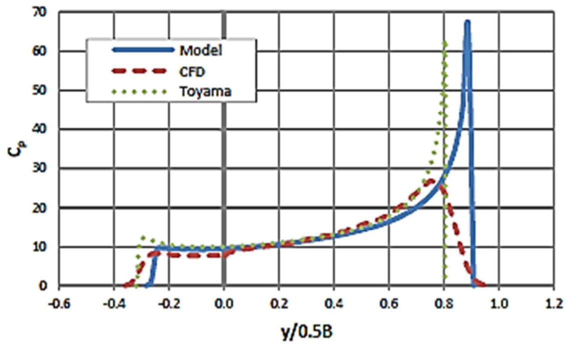

Figure 6: Pressure distribution for $\beta_1 = 10$ and $\beta_2 = 30$

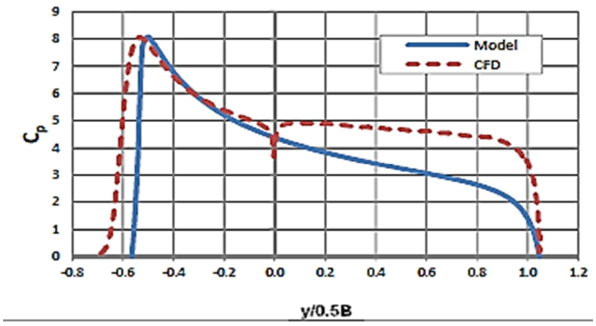

Figure 7: Pressure distribution for $\boldsymbol{\beta_1 = 10}$ and $\boldsymbol{\beta_2 = 30}$

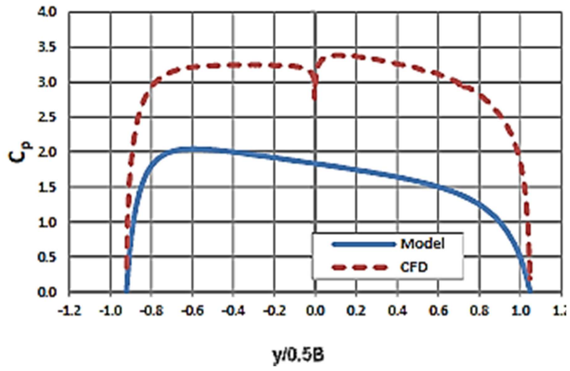

Figure 8: Pressure distribution for $\beta_1 = 10$and $\beta_2 = 30$

The horizontal and vertical forces are calculated by integrating the pressure on any section.

Figure 9 shows the variation the vertical force during the impact for a wedge section with β_1=20° and β_2=30°, the results are compared with Xu et.al. (1998) work and CFD modeling, the current model shows a good agreement with the other authors.

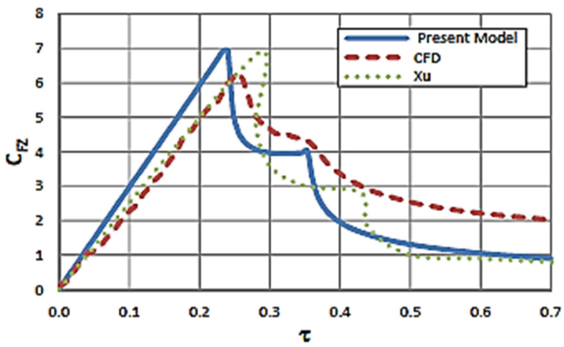

Figure 9.variation of vertical force for β_1=20° and β_2=30°

4.0 CONCLUSIONS

In this paper, we first reviewed and analyzed wedge symmetrical impact to the surface, then problem of two dimension wedge section asymmetrical impact to the surface of water was studied. To analyze the mentioned phenomenon in asymmetrical mode, number of analyzed relationships were used that how to achieve these relations has been mentioned briefly. Finally, the obtained analytical relations to determine the pressure distribution and its maximum value on wedges with different deadrise angles were applied. The results showed good agreement between the results and the results of other researchers study. Finally by analyzing the results, pressure distribution response related to geometric and physical changes in impact problem were studied.

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