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A Modified Logvinovich Model For Hydrodynamic Loads on an Asymmetric Wedge Entering Water with a Roll Motion

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Abstract: The water entry problem of an asymmetric wedge with roll motion was analyzed by the method of a modified Logvinovich model (MLM). The MLM is a kind of analytical model based on the Wagner method, which linearizes the free surface condition and body boundary condition. The difference is that the MLM applies a nonlinear Bernoulli equation to obtain pressure distribution, which has been proven to be helpful to enhance the accuracy of hydrodynamic loads. The Wagner condition in this paper was generalized to solve the problem of the water entry of a wedge body with rotational velocity. The comparison of wet width between the MLM and a fully nonlinear numerical approach was given, and they agree well with each other. The effect of angular velocity on the hydrodynamic loads of a wedge body was investigated.
Keywords: water entry; roll motion; modified Logvinovich model(MLM); asymmetric wedge
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1 Introduction

Water entry problem, related with many physical phenomena and strong engineering background, is an important and valuable research direction. One of the most significant applications is the slamming of ship. Especially, for both very large ship and planning ship, slamming is a key factor which noticeably influences the safety and comfort. The landing of seaplane is the engineering background based on which the Von Karman's model (Von Karman, 1929) and the Wagner model (Wagner, 1932) are introduced. Both of them also serve as the fundamental analytical models in the field of water impact. Green water problem and some other phenomena associated with the case that water impacts structures also have similar analysis methods as that of water entry problem.

Although there are numerous kinds of practical application of water entry problem, the analytical models of them can be easily categorized physically. Based on different key points that people care about, models of water entry problem contain various assumptions, which can also be used as criterions for classification. Assumptions are usually introduced from four aspects: dimension of the problem, structure, fluid and the process of impact. First of all, one of the most important aspects of the whole water entry problem is the dimension of the model. Three-dimensional model can give more accurate results, but at the same time it's so difficult to calculate the motion of flow in three-dimensional coordinate that there is no suitable method for general three-dimensional problem until now. Second, for structure part, shape and stiffness are two keys people care about. Except for the real shape of structure, analytical models always assume the shape, in two-dimensional problem, to be wedge body, blunt body (or wedge body with very small deadrise angle) or plate body, because most of the real shape of structures can be included in these three kinds of body shape and each of them has distinct characteristic. For plate body, air bubble effect should be taken into account and for blunt body, the compressibility of liquid at the initial time may affect the hydrodynamic loads (Korobkin, 1992). Moreover, the stiffness of body has relation with the issue whether we should consider the effect of hydroelasticity and the vibration of ship hull. Third, for fluid part, the main assumption is that the liquid is incompressible and ideal. However, if one tends to calculate the water entry problem of real shape and the separation point of jet flow, gravity, viscosity and even surface tension of liquid are supposed to be considered. Up to now, it is still a tough problem to take all these factors into account. Further, whether to consider compressibility of fluid should depend on whether the velocity of contact points of surface of body and free surface is close to or larger than the acoustic velocity (Korobkin, 1992). At last, for the process of impact, the main limitations are the number of degree of freedom and the variability of velocity. When the velocity of body is no longer constant, similarity method cannot be applied anymore, so some decoupling means such as that adopted by Xu *et al*. (2010) should be used. However, it is known that the duration of impact process we care about is so short that the assumption that velocity is constant is reasonable as it stands. Moreover, the degree of freedom determines whether the analytical model can accurately simulate the real phenomena. It is apparent that the water entry problem and slamming that happened at ship bow are always concomitant with the roll motion of ship. In the meantime, the analytical results of this paper confirm that angular velocity can influence

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hydrodynamic loads on body much. Xu *et al*. (2010) took account of the water impact problem with three degrees of freedom by use of fully nonlinear numerical method. In analytical model of this paper, the motion of body is assumed to be in two degrees of freedom: surge and roll; the structure is assumed to be a stiff wedge body; the fluid is assumed to be incompressible and ideal.

Strong nonlinear phenomenon is always one of the greatest challenges in water entry problem. The method for this difficulty, as Hughes (1972) concluded, can be generally grouped into two categories: one is to simplify boundary conditions reasonably and then to obtain analytical results; the other one is to make use of numerical solutions to directly calculate complete boundary-value problem. Dobrovol'skaya (1969) gave a similarity solution based on the Wagner condition. Zhao and Faltinsen (1993) solved this problem by means of boundary element method and an advisable truncation method at the jet flow region. Xu *et al*. (2008) presented fully nonlinear numerical results using boundary element method for oblique entry of an asymmetric wedge body. All of them are the representative of group two. On the other hand, asymptotic analysis is the major method in group one. Howison *et al*. (1991) divided the flow region into three parts and introduced different small parameter in each part using matched asymptotic method to solve nonlinearity of the fluid part. After that, some combined solutions are presented, which applied numerical method to solve, to some extent, simplified analytical model. Zhao *et al*. (1996) gave a generalized Wagner model, which linearizes the condition of free surface, and made use of boundary element method to simulate structure. Vorus's model (Vorus, 1996) introduced approximated plate approach to describe body and consider the nonlinearity in other regions by means of numerical method. Most of analytical models mentioned above are based on the Wagner model. Korobkin (2004) gave an excellent conclusion of those models and presented a modified Logvinovich model (MLM), which is based on the Logvinovich's model (Logvinovich, 1969). MLM linearizes both the body boundary condition and the free surface condition based on the asymptotic method but applies nonlinear Bernoulli formula. Meanwhile, this proposal applies Taylor expansion to obtain a modified form of velocity potential instead of that of classical Wagner model. In the comparison with experiment results on hydrodynamic force by Iafrati and Battistin (2003), MLM shows good agreement. After that, Korobkin and Malenica (2005) generalized MLM to account for water entry of asymmetric contours. In this case, the hydrodynamic loads calculated by MLM present fine accordance with experimental results as well.

This paper further generalizes MLM to deal with the problem of asymmetric wedge entering water with rotational velocity. This is for the first time to consider roll motion during water impact process using analytical model. Wagner condition is modified to cover the angular velocity of body. The effect of the rotational velocity on hydrodynamic loads during water entry is studied.

2 Formulation of the problem

In this section, the formulas of wedge body entering water with roll motion are derived. Asymptotic method for velocity potential, Wagner condition for varied wet width of body and the nonlinear Bernoulli formula for the pressure distribution along wet surface are given. Because the duration of impact we care about is very short and the velocity of flow is much less than acoustic velocity, liquid is assumed to be incompressible, non-viscous and the gravity and surface tension can be neglected. The depth of liquid region is infinite. At the initial time, water is at rest and the liquid region is $y \le 0$; the body touches the free surface at a single point ($x = 0$) which is taken as the origin of the Cartesian coordinate system Oxy; the deadrise angle of wedge body is γ and inclination angle is σ (see Fig.1). The rotational center is supposed to be at the apex of the wedge body. The angular velocity is ω and the vertical velocity is V, both of which are assumed to be constant. Here we take σ as positive when it turns clockwise and take $\theta = \omega t$ as positive when it turns anticlockwise. So the actual deadrise angle on the right side of wedge body is $\gamma_R = \gamma - (\sigma - \theta)$ and on the left side is $\gamma_L = \gamma + (\sigma - \theta)$. Further, in case of both the immerging of edge of the wedge and the appearance of multivalued function, $\gamma > |\theta - \sigma|$ and $2\gamma < \dfrac{\pi}{2}$. Therefore, body shape can be written as

$$f(x,\theta) = \delta x \tan(\gamma - \delta(\sigma - \theta)), \quad \delta = \begin{cases} 1, x \ge 0 \\ -1, x < 0 \end{cases} \tag{1}$$

And the position of the body is described as $y = f(x,\theta) - h(t)$, where $h(t)$ is the vertical displacement and $h(t) = Vt$.

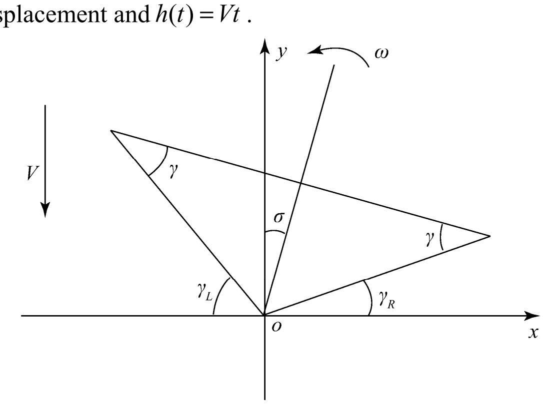


Fig.1 Initial position of wedge and free surface

2.1 Asymptotic analysis

To obtain the velocity potential of fluid during the impact of wedge body with roll motion, asymptotic method is used.

According to MLM by Korobkin (2004), because the vertical displacement h is of the same order as $f(L,\theta_0)$ and is small compared to the horizontal size of the contact region L for body with small deadrise angle, we take $\varepsilon = f(L,\theta_0)/L$ as the small parameter. $f(L,\theta_0)$ is regarded as the vertical position of the contact point between water surface and body surface at the time t, when the horizontal size of wetted breadth is 2L and rotational angle is θ_0. L is also introduced as the length scale. εL is the displacement scale. V is the velocity scale. Then non-dimensional variables can be obtained (η is the shape function of free surface):

$$\bar{x} = x/L;\ \bar{y} = y/L;\ \bar{\varphi} = \varphi/LV;\ \bar{t} = \frac{t}{\varepsilon L/V};$$

$$\bar{h} = h/\varepsilon L;\ \bar{\eta} = \eta/\varepsilon L;\ \bar{f}(\bar{x},\theta) = f(x,\theta)/\varepsilon L.$$

Therefore, the non-dimensional velocity potential should satisfy Laplace equation and boundary conditions as follows,

$$\Delta\bar{\varphi} = 0,(\bar{y} < 0) \tag{2}$$

$$\frac{\partial\bar{\varphi}}{\partial t} + \varepsilon\frac{1}{2}|\nabla\bar{\varphi}|^2 = 0,(\bar{y} = \varepsilon\bar{\eta}(\bar{x},\bar{t})) \tag{3}$$

$$\frac{\partial\bar{\eta}}{\partial t} + \varepsilon\frac{\partial\bar{\eta}}{\partial\bar{x}}\frac{\partial\bar{\varphi}}{\partial\bar{x}} = \frac{\partial\bar{\varphi}}{\partial\bar{y}},(\bar{y} = \varepsilon\bar{\eta}(\bar{x},\bar{t})) \tag{4}$$

$$\frac{\partial\bar{\varphi}}{\partial\bar{y}} = \varepsilon\bar{f}_x\frac{\partial\bar{\varphi}}{\partial\bar{x}} - \frac{\partial\bar{h}}{\partial t} + \bar{f}_\theta\theta_{\bar{t}},(\bar{y} = \varepsilon[\bar{f}(\bar{x},\theta) - \bar{h}(\bar{t})]) \tag{5}$$

$$\bar{\varphi} \to 0,(\bar{x}^2 + \bar{y}^2 \to \infty) \tag{6}$$

Where, $f_\theta\theta_t = \dfrac{\omega x}{\cos^2(\gamma - \delta(\sigma - \theta))}$.

The approximation of velocity potential is very similar to MLM by Korobkin (2004), which is based on the Taylor expansion, but because of the existence of last term in equation (5), the expression of potential is changed:

$$\varphi(x,t) = \varphi^{(w)}(x,0,t) - (\dot{h}(t) - f_\theta\theta_t)[f(x,\theta) - h(t)] \tag{7}$$

Where $\varphi^{(w)}(x,0,t)$ comes from the classical Wagner model. But in this problem, because of the existence of angular velocity ω, classical Wagner model should change as follows (to ignore the $O(\varepsilon)$ terms in equations (2)-(6)):

$$\Delta\varphi^{(w)} = 0,(y < 0) \tag{8}$$

$$\varphi_t^{(w)} = 0,(y = 0, x > a(t) or x < -b(t)) \tag{9}$$

$$\varphi_y^{(w)} = -\dot{h} + f_\theta\theta_t,(y = 0, -b(t) < x < a(t)) \tag{10}$$

$$\varphi_y^{(w)} \to 0,(x^2 + y^2 \to \infty) \tag{11}$$

$$\eta_t = \varphi_y,(y = 0, x > a(t) or x < -b(t)) \tag{12}$$

Where $y = 0, -b(t) < x < a(t)$ describes the contact region in Wagner model based on flat-disc approximation. To solve equations (8)-(11), we use complex velocity method and introduce Hilbert formula. Then, we obtain the velocity potential under the classical Wagner model with roll motion.

$$\varphi^{(w)} = -\dot{h}\sqrt{(b+x)(a-x)} + \frac{\omega}{\cos^2(\alpha)}\frac{\sqrt{(b+x)(a-x)}}{4}(3a - 3b + 2x) \tag{13}$$

Where, $\alpha = \gamma - \delta(\sigma - \theta), \delta = \begin{cases} 1, x > 0 \\ -1, x < 0 \end{cases}$.

In the latter equation, the body shape function has been introduced. Thus, equation (7) can be transformed to

$$\varphi(x,t) = -\dot{h}(t)\sqrt{(a-x)(b+x)} - \dot{h}(t)[\delta x\tan(\alpha) - h(t)] + \frac{\omega}{\cos^2(\alpha)} \times \left[\frac{\sqrt{(b+x)(a-x)}}{4}(3a - 3b + 2x) + \delta x^2\tan(\alpha) - xh(t)\right] \tag{14}$$

The above equation is the final form of velocity potential in MLM for wedge body with angular velocity. The main difference between expressions of potential in general MLM and in this condition is the existence of the third term in the right-hand side of the equation, so this term describes the influence on the velocity potential of roll motion. And if we assume the rotational velocity to be zero, equation (14) is the same as that derived by Korobkin and Malenica (2005) in the case that inclined wedge entering water without roll motion by the method of MLM. In this equation only $a(t)$ and $b(t)$ are unknowns and they can be obtained by the use of Wagner condition in the next section.

2.2 Calculation of wet width

Wagner condition is introduced in this section to obtain the value of $a(t)$ and $b(t)$.

$$\left.\begin{aligned} \eta(a(t),t) &= f(a(t),\theta(t)) - h(t) \\ \eta(-b(t),t) &= f(-b(t),\theta(t)) - h(t) \end{aligned}\right\} \tag{15}$$

To solve the Wagner conditions (15) above, we introduce a displacement potential Φ. Thus this displacement potential should also satisfy Laplace equation and boundary conditions as follows.

$$\Delta\Phi = 0,(y < 0) \tag{16}$$

$$\Phi = 0,(y = 0, x > a(t), x < -b(t)) \tag{17}$$

$$\Phi_y = f(x,\theta(t)) - h(t),(y = 0, x > a(t), x < -b(t)) \tag{18}$$

$$\Phi \to 0,(x^2 + y^2 \to 0) \tag{19}$$

By using the similar method to solve the equations (8)-(11), we can transform the Wagner conditions (15) to new forms which are similar to that derived by Korobkin and Malenica (2005).

$$\int_{-1}^{1}[f(x(\tau),\theta(t))-h(t)](\frac{1+\tau}{1-\tau})^{\frac{1}{2}}\mathrm{d}\tau=0 \tag{20}$$

$$\int_{-1}^{1}[f(x(\tau),\theta(t))-h(t)](\frac{1-\tau}{1+\tau})^{\frac{1}{2}}\mathrm{d}\tau=0 \tag{21}$$

$$x(\tau)=A(t)\tau+B(t),$$

$$A(t)=\frac{1}{2}(a+b)\,,\,B(t)=\frac{1}{2}(a-b).$$

Therefore, $a(t)$ and $b(t)$ can be obtained and their expressions are just as the equation (14) given by Korobkin and Malenica (2005).

$$a(t)=a_0h(t)\,,\,b(t)=b_0h(t) \tag{22}$$

$$a_0=\frac{\pi}{2\tan(\gamma-\sigma+\theta)}\frac{1-\varepsilon}{(1-\mu)\sqrt{1-\mu^2}}\,,\,b_0=a_0\frac{1-\mu}{1+\mu}$$

μ is given by the equation

$$\mu\sqrt{1-\mu^2}+\arcsin\mu=\frac{\pi\varepsilon}{2}$$

The only difference is that the form of ε is transformed.

$$\varepsilon=\sin(2(\sigma-\theta))/\sin(2\gamma)$$

To get pressure distribution in the next section, we should also know the derivative of $a(t)$ and $b(t)$.

$$\dot{a}=a_0(\lambda,\gamma)[N_a(\lambda,\gamma)\dot{\lambda}h+\dot{h}]$$

$$\dot{b}=b_0(\lambda,\gamma)[N_b(\lambda,\gamma)\dot{\lambda}h+\dot{h}]$$

Where, $\lambda=\sigma-\theta$,

$$N_a(\lambda,\gamma)=\frac{2}{\sin[2(\gamma-\lambda)]}+$$

$$\frac{\pi}{2}\frac{\cos(2\lambda)}{\sin(2\gamma)}\frac{1}{(1-\mu^2)^{3/2}}[1+2\mu-\frac{4}{\pi}\frac{(1-\mu^2)^{3/2}}{1-\varepsilon}]$$

$$N_b(\lambda,\gamma)=N_a(\lambda,\gamma)-\pi\frac{\cos(2\lambda)}{\sin(2\gamma)}\frac{1}{(1-\mu^2)^{3/2}}.$$

2.3 Calculation of pressure and hydrodynamic loads

The pressure in the flow region can be obtained by the Cauchy-Lagrange integral.

$$p(x,y,\theta,t)=-\rho(\varphi_t+\frac{1}{2}|\nabla\varphi|^2) \tag{23}$$

ρ is the water density. Here we define

$$P(x,\theta,t)=p(x,f(x,\theta)-h(t),t)$$

$$\phi(x,\theta,t)=\varphi(x,f(x,\theta)-h(t),t)$$

The latter equations together with boundary condition on the body surface can give

$$P(x,\theta,t)=-\rho(\phi_t+\frac{f_x\dot{h}}{1+f_x^2}\phi_x+\frac{1}{2}\frac{\phi_x^2-\dot{h}^2+f_\theta^2\theta_t^2}{1+f_x^2}) \tag{24}$$

We can see the last term in the right-hand side of the above equation is different from general MLM. $f_\theta^2\theta_t^2$ is the additional term, which just exists in nonlinear Bernoulli equation. So if we adopt Wagner model here, this term will be ignored, which inevitably influences the accuracy of the results.

According to MLM, when calculating hydrodynamic force by integrating pressure along wet surface, we only take the positive pressure value into account, which because, in the region near contact points, the pressure tends to negative infinite. Thus, we have equation for hydrodynamic force as follows.

$$F(t)=\int_{-\tilde{b}(t)}^{\tilde{a}(t)}p(x,\theta,t)\mathrm{d}x \tag{25}$$

Where, $p(\tilde{a}(t),\theta,t)=0$ and $p(\tilde{b}(t),\theta,t)=0$. Here, $\tilde{a}(t)$ and $\tilde{b}(t)$ can be obtained by the method of bisection. $F(t)$ is evaluated by the Romberg integral method.

3 Results and comparisons

When rotational velocity $\omega=0$ whether for asymmetric or for symmetric wedge, the equations both for pressure and force in this paper are the same as those of MLM given by Korobkin (2004, 2005). Validation for simple case (water entry problem of symmetric wedge) has been given by Korobkin (2004). Further, Korobkin and Malenica (2005) gave comparisons of results of hydrodynamic force between MLM and experiment for asymmetric case without rotation, which also revealed good agreement. Moreover, it is well known that when it comes to the problem of pressure distribution, MLM as well as other analytical models can have a good agreement with numerical results only when the deadrise angle is small due to the linearization of the formulae and the appearance of singular point. But, the results of hydrodynamic loads of analytical models always show excellent agreement with experimental and numerical ones. Therefore, we mainly focus on the results of hydrodynamic loads of this new model. In this section, for the reason that there is rarely exact the same model as the one calculated in this paper, we just present the comparisons of wet width of Wagner model and MLM with numerical results by Xu *et al*. (2010), in whose paper the deadrise angle of the calculated wedge is a little larger than the expected one and there is no result of hydrodynamic loads. In the second part of this section, hydrodynamic loads in different cases are presented.

3.1 Comparisons of wet width

This paper generalizes the Wagner condition to the case of water entry with roll motion to obtain wet width of wedge body. It is know that even in the second order theory of water impact problem, the contact width calculated by Wagner condition remains the same form as that in the first order theory (Korobkin, 2007). That is to say, Wagner condition gives adequate accuracy in predicting wet width of wedge body even in the first order method.

However, it has been justified that, according to Wagner model, in the near region of contact point between water surface and body surface, the pressure tends to be negative infinity unreasonably. Therefore, in order to avoid this irrational phenomenon, in the calculation of hydrodynamic force, MLM adopts the points at which the pressure is equal to zero instead of that obtained by Wagner condition as boundary. Figure 2 compares the results of wet width between MLM and numerical approach given by Xu *et al.* (2010), which matches each other very well.

Fig.2 describes the case of the water entry of a wedge body with constant velocity and rotational velocity, initial deadrise angle $\gamma = \pi/4$, inclination angle $\sigma = -\pi/9$, vertical velocity $V = 5\text{m/s}$, rotational velocity $\omega = -2.5\text{rad/s}$, $P' = P/\rho$.

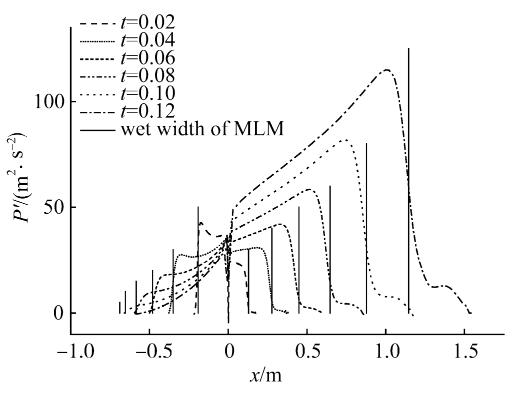


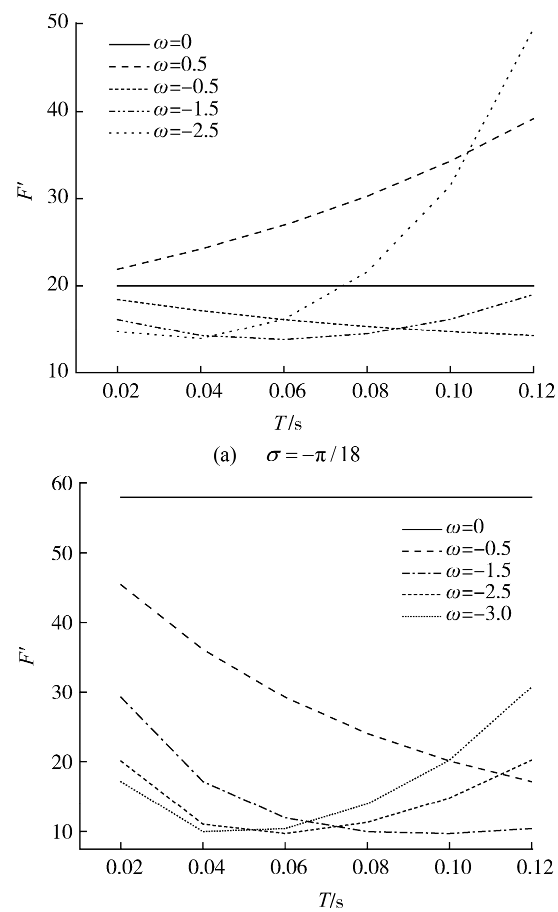
Fig.2 Comparisons of wet width

3.2 Results of hydrodynamic loads

In the paper of Korobkin and Malenica (2005), the hydrodynamic force of wedge body entering water with inclination angle was obtained using MLM, and matched well with experimental results. In present paper, we also calculate the non-dimensional hydrodynamic load when wedge body impacts water surface with just inclination angle but no rotational velocity, and find it is nearly equal to the result of fully nonlinear numerical approach by Xu *et al.* (2008). In the case $\gamma = \pi/6$ and $\sigma = \pi/18$, both of methods give results which are very close to 20.

Then, non-dimensional hydrodynamic loads in different rotational velocity cases and different inclined angle are calculated. From Fig.3, it can be illustrated that when wedge body enters water with inclination angle, if there is a small angular velocity which turns against the initial inclined angle, then the hydrodynamic force goes down, but if the angular velocity becomes faster, the loads goes large again. Meanwhile, the larger the inclination angle, the faster the angular velocity needed to reduce the hydrodynamic loads.

Fig.3 gives the non-dimensional hydrodynamic force of wedge entering water with different angular velocity and with different initial inclination angle. $\gamma = \pi/6$, $V = 5\text{m/s}$ and $\sigma = -\pi/18$ for (a), $\sigma = -\pi/9$ for (b), $F' = F/\rho V^2 Vt$.



(a) $\sigma = -\pi/18$

(b) $\sigma = -\pi/9$

Fig.3 Results of hydrodynamic loads

4 Conclusions

This paper makes use of MLM to solve the problem of the water entry of wedge body with roll motion. This issue is studied for the first time by analytical method and the Wagner condition is generalized to account for water impact problem with angular velocity. The modified Wagner condition can also be adopted in other analytical approaches to calculate wet width of body. The results of contact width of wedge body and free surface obtained by this generalized Wagner condition are compared to that of numerical solution. As a consequence, it presents good agreement between two schemes, which confirms the accuracy of wet width given by Wagner condition. The simple comparison between the results of the MLM and numerical method on hydrodynamic loads of water entry problem without rotation is made. It shows good agreement. Hydrodynamic loads are also presented in different rotational velocity cases. It reveals that small angular velocity which turns against the initial inclination angle is useful to reduce the total hydrodynamic loads of wedge body.

The model of this paper is still in compulsive motion, which does not correspond with the majority of natural phenomenon. So in the next step, the model is expected to be further generalized to solve free fall case. Moreover, some experimental or numerical results of hydrodynamic force in the same conditions are needed for comparison.

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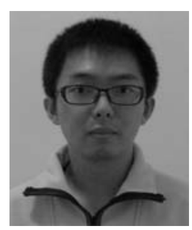

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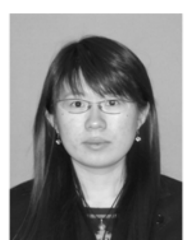

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