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Research Article

Simulation Analysis of Wave Effect on Exceeding Water Gesture and Load of Submarine Launched Missile

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Abstract: In this study, we have a research on wave action on the submarine launched missile water trajectory and gesture angles during the process between launch and exit from water. Infinite water depth plane wave was used as the wave model, mathematics models of missile exceeding water under different wave conditions were established based on ideal potential flow theory. The flow field velocity potential was obtained by solving the Laplace equation, thus can obtain missile surface pressure. Considering free surface effects, simple Green's function was introduced to solve boundary value problems. Three-dimensional Fortran program and finite software ABAQUS were combined to complete the fluid-structure interaction simulation. The rules that wave level and phases effects on submarine-launched missile were finally obtained, which shows wave affect cannot be neglected. Simulation methods and results of this study have a certain reference value for the submarine-launched missile launching.

Keywords: Fluid-structure interaction, gesture angle, hydrodynamic load, simulation, wave effect, water trajectory

INTRODUCTION

Submarine launched missile is attached great importance to at home and abroad because it has the advantages of strong concealment and high percentage. The missile entries the air to experience 2 stages after it releasing from carrier the underwater operation free running phase and the water-exit phase, which are affected by various factors. Firstly, during the underwater operation free running phase the marine environment loads such as wave load will add to the missile. Secondly, water-exit process involves two phase environments where medium mutation will lead to the force on the missile changes. And the change of load will cause trajectory and gesture angle change even structure destruction, thus directly impact the missile launching, so accurately determine the load on the missile during water-exit process is very important. And at the real ocean circumstance, wave motion usually presents and cannot be ignored and with the randomness and superficiality of whom will make the water-exit process more complex. Therefore, the missile load analysis involving wave motion will be more close to the engineering practical situation.

So far, there have been many studies on wave and structure interaction, the mathematical models to solve such problems are basically based on ideal potential flow model or N-S model. For the ideal potential flow model, the most widely used solving methods are BEM (boundary element method) and FEM (finite element method), simple two-dimensional problems were firstly and mainly studied. Ferrant and Touzé (2002), Tanizawa (1995) and Tanizawa *et al*. (1999) used BEM to analyze the force acting on an all free floating body under incident waves, Wu and Taylor (1995) and Hong and Nam (2011) used FEM to study the interaction of two-dimensional nonlinear wave and structure and also the wave diffraction characteristics. With the deepening of research, the researches of three-dimensional problems were also gradually spread. Ma (1998) and Li and Ye (2005) used FEM to study the interaction of three-dimensional nonlinear wave and structure, Sun (2010) used NDAA method to study high frequency fluid-structure coupling problem including free surface effect and fluid compressibility. For the N-S model, with the development of large-scale commercial software, the users can use the software to solve the N-S equation directly (Chen and Yu, 2009; Nam *et al*., 2011) but it will consume too much time to improve too little accuracy when no wave breaking. However, no matter what the theory model we use, the studies that specifically aimed at the fluid-structure problems of missile and wave are still limit, while the researchers studying on the missile loading characters under different wave phases are more lack of.

Therefore, in this study, specific missile water-exit mechanical model under wave action is established based on the potential flow theory (Dai and Duan, 2008). Self-designed 3-D program and FEM software are used to mathematically simulate the fluid-structure coupling process of submarine-launched missile exiting water. The results are compared with the live ammunition simulation experimental data. It is proved that the self-designed program is efficient. So finally,

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we get some valuable rules of wave parameters (wave scales, phases) effecting on the missile loading, trajectory and gesture angle.

THEORETICAL MODEL

Wave mathematical model: Sea waves are a kind of periodic motion produced by the effect of gravity under the sea wind disturbance. The actual wave motions are very complex; in order to simplify the problem we took plane wave (Airy wave) as the wave model and made the following assumptions:

- The fluid is an incompressible ideal fluid, the flow is irrotational. There exists velocity potential φ_f and $v = \nabla\varphi_f$
- Gravity is the only force (restoring force)
- Fluid surface pressure is equal to atmospheric pressure
- Missile radial size is far smaller the wavelength
- Wave height is infinitesimal for relatively large wave length and the fluid particle movement is slow
- Seafloor is level solid boundary and depth is infinite

In this study, the wave propagates in the x-z plane of geodetic coordinate system. The plane wave mathematical model in infinite water-depth is:

$$\begin{cases} \varphi_i = \dfrac{gA}{\omega} e^{kz} \sin(kx - \omega t + \varepsilon) \\ \eta(x,t) = A\cos(kx - \omega t + \varepsilon) \end{cases} \tag{1}$$

where, φ_i, λ, T, A, w, k are representatives of the incident wave velocity potential, wave length, cycles, wave amplitude, frequency, wave number.

The velocity of the fluid particle is:

$$\begin{cases} u = \dfrac{\partial \varphi_i}{\partial x} = \omega A e^{kz} \cos(kx - \omega t + \varepsilon) \\ v = \dfrac{\partial \varphi_i}{\partial y} = 0 \\ \omega = \dfrac{\partial \varphi_i}{\partial z} = \omega A e^{kz} \sin(kx - \omega t + \varepsilon) \end{cases} \tag{2}$$

Missile movement mathematical model under waves: Figure 1 shows the missile movement physical model under water. As shown in this figure, rectangular coordinate OXYZ is taken as geodetic coordinate system. XOY plane overlaps with static water plane, *Z* axis is vertical. Missile velocity is *V*. Fluid here follows the assumption in 1.1 (a), Φ represents missile potential velocity in the water which is composed of the missile movement perturbation potential φ_b and wave incidence potential φ_i:

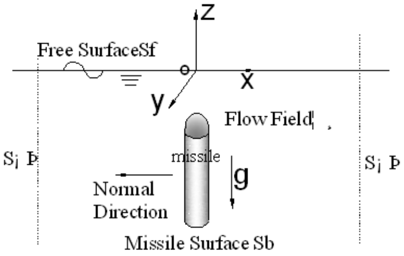


Fig. 1: Physical model

$$\Phi = \varphi_b + \varphi_i \tag{3}$$

When t>0, the total velocity potential of flow field, wave incidence potential and perturbation potential can all satisfy the Laplace equation:

$$\nabla^2 \Phi = 0,\ \nabla^2 \varphi_b = 0,\ \nabla^2 \varphi_i = 0 \quad \text{(in flow field)} \tag{4}$$

The following boundary conditions must be met:

The infinite boundary condition:

$$\nabla\Phi \to \nabla\varphi_i\ ;\ \Phi \to \varphi_i \ \text{(on } S_\infty\text{)} \tag{5}$$

The boundary condition on the body:

$$\frac{\partial \varphi_b}{\partial n} = V_b \cdot \mathbf{n} - \frac{\partial \varphi_i}{\partial n} \quad \text{(on } S_b\text{)} \tag{6}$$

where V_b is the velocity of missile, n is the normal directions on the missile surface.

In addition to meet the boundary condition above, the free surface boundary condition Eq. (7) also must be met when free surface is taken into consideration:

$$\frac{\partial^2 \varphi_i}{\partial t^2} + g\frac{\partial \varphi_i}{\partial z} = 0 \quad \text{(on } S_f\text{)} \tag{7}$$

In every moment, once the boundary conditions are identified, the corresponding physical quantities of each point in the field can be determined as well. After the flow field potential velocity Φ obtained, the dynamic pressure on the body surface is given by the unsteady Bernoulli equation Eq. (8):

$$p_d = -\rho\left(\frac{\mathrm{D}\Phi}{\mathrm{D}t} - \mathbf{V}\cdot\nabla\Phi + \frac{1}{2}\cdot\nabla\Phi^2 + gz\right) + P_0 \tag{8}$$

where, P_0 represents atmosphere and in this study missile surface pressure is set as an atmosphere after it exiting from water.

Green's function method: In this study, Green's function method is used to compute the velocity potential. Green's function method is called singular point distribution method, boundary integral equation method or boundary element method and it's based on Green's function. By Eq. (8) we know that the key to obtain the surface pressure is to calculate the flow field velocity potential Φ. And if we take the wave incident potential as a known input, then the problem is transformed to calculate the missile movement perturbation potential φ_b according to Eq. (3).

According to Green's function, with the given values of boundary function and the normal derivatives, the values of potential function in any point of the flow field can be found. Boundary integral equation is as follows:

$$4\pi\varphi_b(p_0) = \iint_s \left(\frac{\partial \varphi_b(q)}{\partial n} G(p_0, p) - \varphi_b(p) \frac{\partial}{\partial n} G(p_0, p) \right) ds \quad \text{(in basin } \Omega\text{)} \tag{9}$$

where, S represents all boundaries including the missile surface, $p_0(x, y, z)$ and p (ξ, η, ζ) are representatives of fix point and integral point.

The needed Green's function must meet the following boundary conditions:

$$\begin{cases} \text{Laplace equation} & \nabla^2 G = 0 \\ \text{The free surface boundary condition} & \dfrac{\partial^2 G}{\partial t^2} + g\dfrac{\partial G}{\partial z} = 0 \quad (\text{on } S_f) \\ \text{Infinit condition} & G = \dfrac{\partial G}{\partial \tau} = O\left(\dfrac{1}{r_{p_0 p}{}^3}\right) \quad (r_{p_0 p} \to \infty) \\ \text{Initial conditions} & G|_{\tau=0} = 0, \left.\dfrac{\partial G}{\partial \tau}\right|_{\tau=0} = 0 \quad (\tau < 0) \end{cases} \tag{10}$$

So we set Green function as $G(p_0, p) = G^0(p_0, p) = r_{pop}{}^{-1}$.

In this study, free surface effecting is considered, so $S = S_f + S_b + S_\infty + S_d$ (S_d is the bottom), thus there will appear an integral on S_f in Eq. (9). In order to avoid the singularity, we select $G^1(p_0, q) = -\tilde{r}_{p0q}{}^{-1}$ as the free surface correction, where point q is point p's symmetric point about x-y plane. So in this study we finally take $G(p_0. P) = G(p_0, p) + G^1(p_0, q) = r_{p0p}{}^{-1} - \tilde{r}_{p0}{}^{-1}$ as Green's function instead.

NUMERICAL METHOD VERIFICATION

Missile water-exit process is a complicated fluid-structure coupling process (Fig. 2). In order to simulate this process, we first take FEM software ABAQUS as structure solver while self-designed 3-D program as hydrodynamic solver. Then we input structural motion response to hydrodynamic solver and calculate the structure hydrodynamic load though Green's function. Next we input this hydrodynamic load to structure solver to calculate structural motion response through the structural dynamics equation and regard this motion response as the input of hydrodynamic solver in the next time step. In this way, we achieve jointly running the two solvers and looping over the calculation, and the fluid-structure coupling process of missile exiting water is simulated.

To verify the effectiveness of the numerical method, we compare the numerical data with the comparison of the live ammunition simulation experimental data (Sun, 2010) and the comparison result is shown as Fig. 3 where C_p represents the dimensionless node pressure. As we can see, the numerical results of node pressure agree well with the experimental results. Unfortunately for the pitch angle, the experimental results are changing linearly while the numerical results are bigger early in the water-exit process, and the nearer the missile approximates to the free surface the faster they increase. That may be caused by the actual fluid velocity, the diffidence of

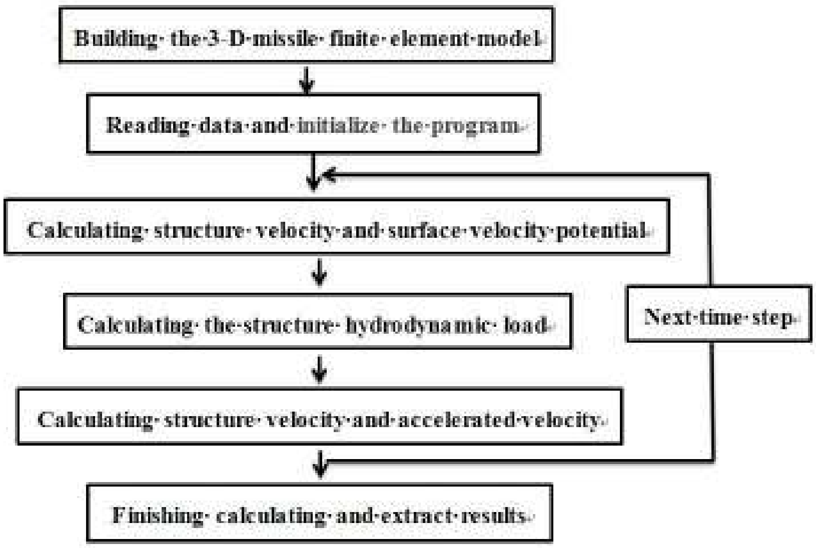
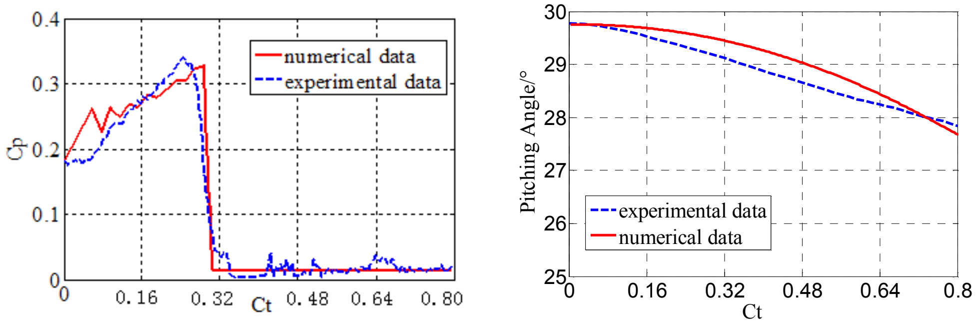


Fig. 2: Configuration of fluid-structure coupling process



(a) Node pressure

(b) Pitch angle

Fig. 3: The compare between the calculation result and the experimental data

mass distribution, the launching subs effect, and numerical error. However, in general, the numerical simulation results are in good agreement with the experimental results. Consequently numerical analysis program is effective.

RESULTS AND ANALYSIS OF WAVE EFFECT

The value of wave force is not only related to the wave scale but also related to wave phase angle. What's more, the value and direction of wave force change together with the wave phase angle. So when analysis the wave effect on missile water-exit process, the wave phase angle is must also be taken into consideration as well as wave scale.

Calculation conditions: In this study, the missile is launched 20 m under water with no submarine speed and vertical launch velocity of 25 m/s. The load, trajectory, gesture angle of missile exiting through different phases of grade 3 and grade 5 waves are needed to obtain. A whole wave period is selected for the study and divided in 60º, the position of missile relative to wave surface is shown in Fig. 4. According to the periodicity of wave motion, the phase angles (in this study we use α as the representative) of 0º (the wave crest) and 300 degrees in crest area (0°≤α≤90°and 270°≤ α ≤360°) and 180 degrees (the wave trough) and 240° in trough area (90°<α<270°) are finally selected.

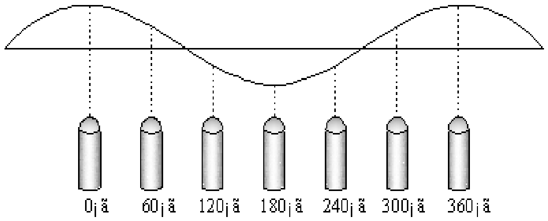


Fig. 4: Relative position between missile and wave surface

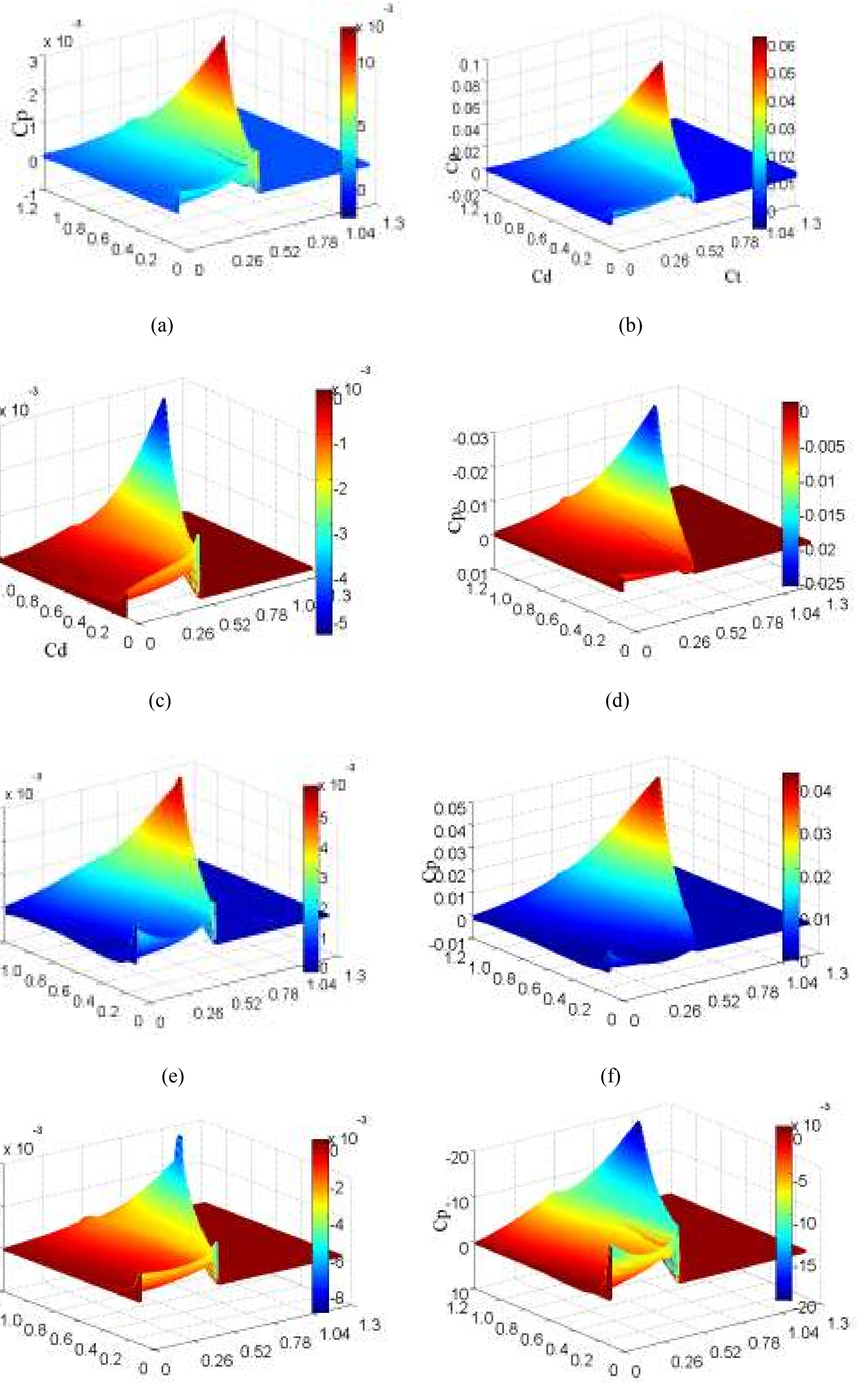
Surface pressure difference: The pressure difference was set to an atmosphere after the missile exit out of water in this study. C_p, C_d and Ct are the representatives of dimensionless pressure differences between meet flow and back flow side, dimensionless missile length, and motion time. As shown in Fig. 5, we know that the pressure differences are positive in the crest area and negative in the trough area. The maximum pressure differences of positive and negative values are appeared in the wave crest and wave trough, and the absolute value in wave crest is bigger than that in wave trough, which shows that the asymmetry of hydrodynamic pressure is bigger in wave crest than that in wave trough. The absolute value of pressures differences increase with the wave scales, and the higher the wave scale is the more intense they increase. In addition, the nearer the missiles to water surface the faster the pressure difference increase that is because of the superficiality the wave motion has.

Pitching moment coefficient of missile: The pitching moment coefficient of missile m_y is given by Yan (2005):

$$m_y = \frac{M_y}{\frac{1}{2}\rho S L v^2} \tag{11}$$

where, ρ, S, v , L are representatives of fluid density (kg/m^3), cross-section area of missile (m^2), launch speed (m/s), length of missile (m).

The distance between the mass center and the node of missile was set as positive and between the mass center and the after body was negative. The pitching moment coefficients under different wave conditions are shown in Fig. 6, firstly we can see the change rule of pitching moment coefficient agrees with that of the pressure difference, and due to the different wave height and phase angle of different wave conditions, the water-exiting time is also different. Then we can see after the mass center of missile exiting water the pitching moment changes its direction, from positive to



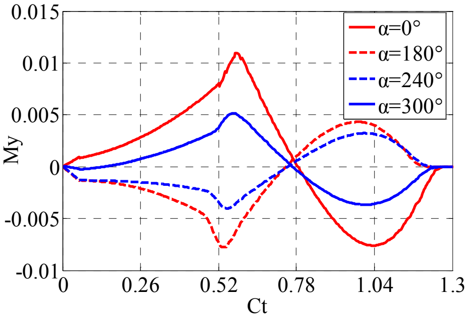
(a) (b)

(c) (d)

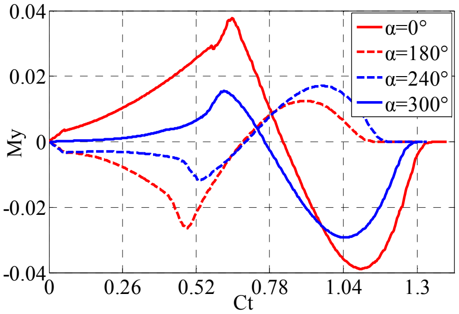
(e) (f)

(g) (h)

Fig. 5: Contour of pressure difference between meet flow side and back flow side, (a) Crest of three grade wave, (b) Crest of five grade wave, (c) 3 grade wave with α = 240°, (d) 5 grade wave with α = 240°, (c) Three grade wave with α = 300°, (f) Five grade wave with α = 300°, (g) Trough of three grade wave and (h) Trough of five grade wave

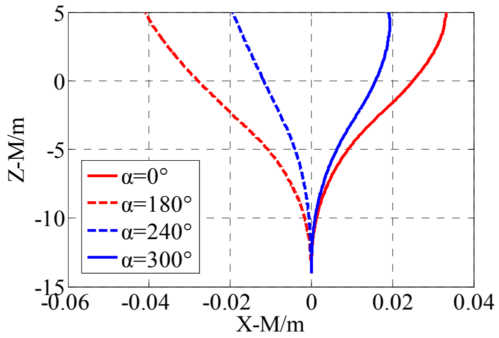


(a) 3 grade wave

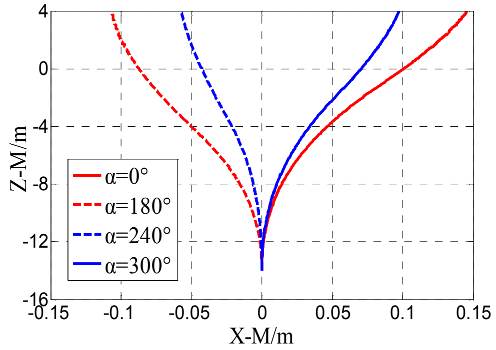


(b) 5 grade wave

Fig. 6: The history curve of pitching moment coefficients under different wave conditions

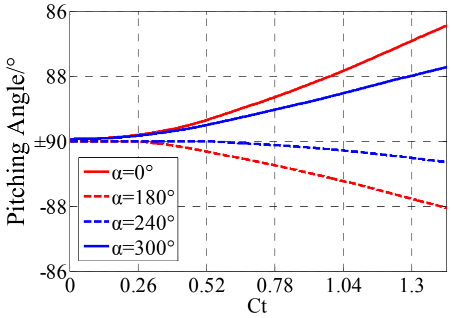


(a) 3 grade wave

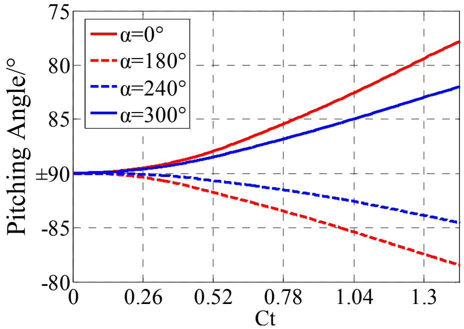


(b) 5 grade wave

Fig. 7: The history curve of the mass center under different wave conditions



(a) 3 grade wave



(b) 5 grade wave

Fig. 8: The history curve of the pitching angle under different wave conditions

negative in crest area and negative to positive in trough area.

Motion of mass center: During the water-exit process, especially when the missile moving across the free surface, the hydrodynamic pressure and buoyancy acting on it will reduce suddenly and together with the additional effect of waves cause an asymmetric force on missile which will make the water trajectory and gesture angle change.

The motion of mass center is shown in Fig. 7 where X-M and Z-M are the representatives of missile X position and Z position. We can see from Fig. 7, the motion of mass center is only about the wave forces of missile when launched with no submarine speed, and the moving direction is the same direction as the wave forces. That is the missile forced positive pressure when in crest area and the mass center moves along X positive direction while the missile force negative pressure when in trough area and the mass center moves along X negative position direction. In addition the offset is bigger in the crest area than that in the trough area, and the positive and negative offset maximum are appeared in crest and trough.

Pitching angle: The pitching angle was set as positive when it was on the right side of Z axis and negative on the left side. As shown in Fig. 8, we can see the pitching angle changes with the wave forces of missile when launched with no submarine speed, and the changing direction is the same direction as wave force, that is pitching angle is positive in crest area while negative in trough area. The offset is bigger in the crest area than that in the trough area, and the positive and negative offset maximum are appeared in crest and trough. In addition, the bigger the wave scale is the faster the pitching angle changes and the bigger the pitching angle differences between different phases are.

CONCLUSION

In this study, based on potential flow theory, the missile water-exiting motion equations including the impact of waves were established, and the wave effects on the missile stress and gestures under different working conditions were analyzed. From the simulation results, we drew conclusions as follows:

- The pressure difference between meet flow side and back flow side increases with the increasing of wave scale, and the bigger the wave scale is the more intense it changes. The waves belong to the gravity wave which means the disturbance of water quality point declines exponentially with the increasing of water depth. So the disturbance will increase near the free surface, namely the nearer the missile approximates to the free surface the faster the pressure difference increase.
- During the process of missile exit water, the surface pressure distribution is related to the wave phase angle. High pressure zone is formed on meet flow side when exit water in crest area and on back flow side when exit water in trough area. The pressure difference is the biggest when in crest, namely in this condition the disturbance of missile is the greatest.
- With the increasing of wave scale, the wave effect on missile becomes more obvious, the asymmetry of force intensifies, which cause the pitching angle and mass center offset increase correspondingly.

In general, through all the analysis above, the effect that waves have on the missile water-exit process mainly displays in the change of pressure leads to the change of trajectory and gesture angle, and which is not only about the wave scale but only about the wave phrase angles.

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