Effects of Deck Motion and Ship Airwake on Ski-Jump Takeoff Performance of Carrier-Based Aircraft

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Abstract: We first analyzed the force and motion of naval aircraft during launching process. Further, we investigated the ship deck with the form of a ramp and established deck motion model and ship airwake model. Finally, we conducted simulations at medium sea. Results showed that the effects of deck motion on takeoff varied with initial phases, and airwake could help reducing aircraft's sinkage. We also found that the deck motion played a major role in the effects caused by the interaction of deck motion and ship airwake.

Key words: ski-jump takeoff; deck motion; ship airwake; sinkage

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0 Introduction

Compared with conventional aircraft, naval aircraft faces a typical challenge: Limited ground distance available for take-off and landing. The two popular techniques used to facilitate aircraft launching safely from a short runway are catapulting and ski-jump[1]. Catapulting provides a large initial momentum for aircraft by a steam piston or an electromagnetic catapult, while ski-jump raises the end of the ship deck to form a ramp therefore to give aircraft an initial climb and pitch rate, which helps aircraft to maintain a safe altitude above the ground before they develops enough velocity and lift to climb away. Ramps have been used in navy ships in many countries for many years to reduce takeoff run distance and wind-over-deck (WOD), as well as to increase the aircraft takeoff gross weight capability better than that of a flat deck carrier[2].

Ski-jump takeoff of carrier-based aircraft is a complex system involving multiple disciplines. The dynamics process of launching customarily consists of movements of the ocean, carriers, aircraft, atmosphere, and all their interactions. Among them, deck motion and airwake impose crucial effects on the process. Many researchers have studied carrier-based aircraft takeoff, but usually trapped in their own fields with supposing and simplifying the effects of other domains. Ref. [3] proposed dynamic models of the whole takeoff process after analyzing the mathematic model and characteristic parameters of ramp runway, and solved the multiobjective optimization problem without any environmental factor. Ref. [4] discussed ship airwake sensitivities to modeling parameters. Accurate models for predicting ship airwake flowfields are critical to practical flight simulation tools for aircraft carrier launch and recovery operations. Ref. [5] showed that the real-time motion of aircraft take-off from the ramp was realized by the software Creator and Vega.

Therefore, we firstly analyzed force and motion of naval aircraft during ramp-assisted takeoff, and established the simplified models . Then we discussed the effects of deck motion and ship

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airwake on ski-jump takeoff performance separately. Finally, we investigated the influence of interactions between deck motion and ship airwake during the launching process.

1 Dynamical Mathematic Model for Ski-Jump Takeoff

Motion equations in ski-jump model are developed by summing aerodynamic forces, conventional ground effects and propulsion forces. Ramp is critical to establish the dynamical mathematic model for ski-jump takeoff of carrier-based aircraft. Typical ramp ski-jump includes three parts: Horizontal acceleration, ramp acceleration and air climbing.

1.1 Ramp deck model

As is shown in Fig. 1, the carrier deck can be transformed into two forms: Horizontal deck and ramp deck, marked as L_p and L_x, respectively. In Fig. 1, $\angle$AOE means the emergence angle and h_m the highest height on ramp deck.

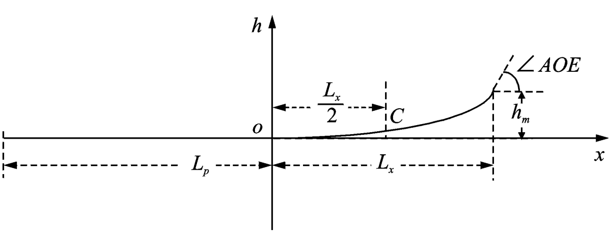


Fig. 1 Cross-sectional shape of carrier deck

The shape of ramp deck is generally described by a three order polynomial as

$$h = ax^3 + bx^2 \quad (1)$$

where $a = 2[\tan\angle AOE - 2\tan(f\angle AOE)]/(3L_x^2)$, $b = [4\tan(f\angle AOE) - \tan\angle AOE]/(2L_x)$, and $f = \dfrac{\arctan\left(\dfrac{3h_m}{2L_x} - \dfrac{\tan(\angle AOE)}{4}\right)}{\angle AOE}$.

1.2 Mathematic model of aircraft during the takeoff process

Due to the special shape of ramp deck, the resultant forces in the aircraft-body coordinate frame vary in the three phases of a typical ramp ski-jump. And force equations and moment equations also follow the change of the relative position between aircraft and naval ship. Nevertheless, the six-degree-of-freedom differential equations of kinematics and dynamics can be described formulas as follows.

(1) Force equations

$$\begin{cases} \dot{u} = vr - wq - g\sin\theta + \dfrac{F'_x}{m} \\ \dot{v} = -ur + wp + g\cos\theta\sin\phi + \dfrac{F'_y}{m} \\ \dot{w} = uq - vp + g\cos\theta\cos\phi + \dfrac{F'_z}{m} \end{cases} \quad (2)$$

where u, v and w are the speed of aircraft in x, y and z directions of the aircraft-body coordinate frame, respectively; p, q and r the rate of roll, yaw and pitch, relating to rotations about the axis x, y and z, respectively; and F'_x, F'_y and F'_z the resultant forces, corresponding to axis x, y and z; θ is the pitch angle and φ the roll angle.

(2) Moment equations

$$\begin{cases} \dot{p} = (c_1 r + c_2 p)q + c_3 \bar{L}' + c_4 N' \\ \dot{q} = c_5 pr - c_6(p^2 - r^2) + c_7 M' \\ \dot{r} = (c_8 p - c_2 r)q + c_4 \bar{L}' + c_9 N' \end{cases} \quad (3)$$

where $\bar{L}'$, M' and N' are the resultant moment relating to rotations about the axis x, y and z, respectively. And the resultant force and moment changes in different processes of ramp-assisted takeoff.

The other two equations, kinematic equations and navigation equations can be seen in Ref. [6].

(3) Kinematic equations

$$\begin{cases} \dot{\varphi} = p + (r\cos\phi + q\sin\phi)\tan\theta \\ \dot{\theta} = q\cos\phi - r\sin\phi \\ \dot{\psi} = \dfrac{1}{\cos\theta}(r\cos\phi + q\sin\phi) \end{cases} \quad (4)$$

(4) Navigation equations

$$\begin{cases} \dot{x}_g = u\cos\theta\cos\psi + v(\sin\phi\cos\psi - \cos\phi\sin\psi) + \\ \qquad w(\sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi) \\ \dot{y}_g = u\cos\theta\sin\psi + v(\sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi) + \\ \qquad w(-\sin\varphi\cos\psi + \cos\phi\sin\theta\sin\psi) \\ \dot{h} = u\sin\theta - v\sin\phi\cos\theta - w\cos\phi\cos\theta \end{cases} \quad (5)$$

where $\phi, \theta, \psi, p, q, r$ are the roll, the pitch, the yaw, the roll rate, the pitch rate and the yaw rate respectively.

During horizontal acceleration, naval aircraft exhibit a motion state similar to the speed skating run movement of land-based plane[7]. And during ramp acceleration, a simplified model can be built by ignoring the landing gear and shoe compression. And assuming that the support force direction of the front and the rear wheels are parallel to each other and both vertical to aircraft wheel baseline, we can get the resultant force and moment during ramp acceleration. Air climbing is the most dangerous stage in the whole ski-jump takeoff process, since it is a link point between ending ramp running and starting normal flying . As a result of the disappearance of conventional ground effects, the model accounts for power-off aerodynamic and propulsive forces.

2 Simulation of Ski-Jump Takeoff without Disturbance

We took F/A-18 as aircraft model. Ship speed was set as 25 kn (about 12.85 m/s), aircraft quality as 20 000 kg, elevator preset angle as −5°, and throttle opening as 1. And the length of the horizontal deck and the ramp deck was 140 m and 60 m, respectively. The simulation was conducted condition that no control system was applied for the sample aircraft model, and the result is shown in Fig. 2.

The simulation lasted 12 s. Fig. 2 well demonstrats ski-jump takeoff. The naval aircraft left the deck at the time of 7.8 s. Then, within 3 s after that the aircraft arrived at the maximum sinkage(2.7 m), and began to climb. With the help of the ramp deck, the plane avoided immediate sinking, but still had to face sinkage, meanwhile, the pitch angle and the attack angle also changed. After the aircraft left the ship, the pitch rate became smaller than that on the ramp deck. And in the process of rising, the maximum angle of attack did not exceed the maximum allowable angle of attack and the speed increased rapidly from 12.85 to 62 m/s, fast enough for the aircraft to leave the ship.

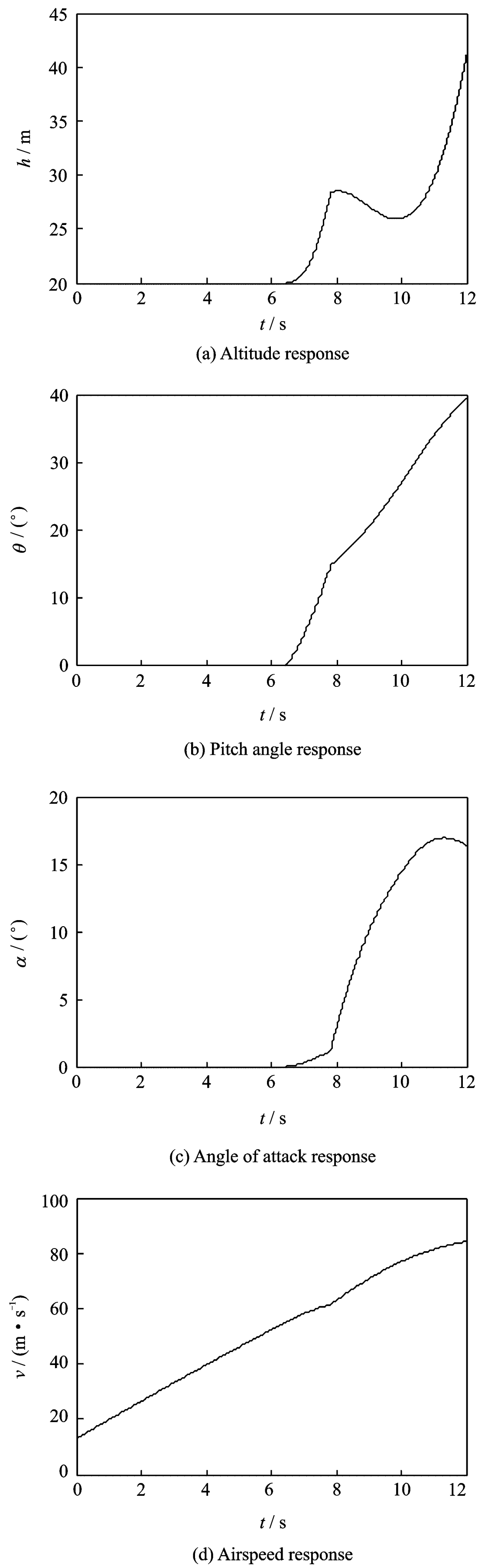


Fig. 2 Simulation curves of ski-jump takeoff

3 Analysis on Effects of Deck Motion on Ski-Jump Takeoff

3.1 Deck motion model

The periodic ship motion due to the effect of sea waves is a special problem of maritime operations[8]. Although ocean currents can generate waves, gravitational and tidal forces and geological phenomena, such as earthquakes, wind, play a major role in producing waves. The typical environmental conditions include wave amplitudes and wave frequency.

The deck model was used to approximate the effects of ship motion in various oceanic conditions. Usually deck motion is dynamically modeled by a six-degree-of-freedom model with motion equations, like the motion of any rigid body. Specifically, the motion of a deck is described in terms of three Euler angles roll, yaw and pitch, relating to rotations around the axis x, y and z, respectively, and three translational terms, surge, heave and sway, corresponding to motions in the x, y and z directions, respectively. And a deck motion model (Eq. (6)) based upon the premise of simple harmonic motion can provide a good enough approximation to the deck conditions

$$y = A\sin(\omega t + \varphi) \tag{6}$$

where A represents the amplitude of the motion, ω the frequency and φ the initial phase.

We presented the specific parameters of the above formula at medium sea conditions.

Plunging motion: $Z_s = 1.22\sin(0.6t) + 0.3\sin(0.2t)$

Pitching motion:

$\theta_s = 0.5\sin(0.6t) + 0.3\sin(0.63t) + 0.25$

Rolling motion:

$\phi_s = 2.5\sin(0.5t) + 3.0\sin(0.52t) + 0.5$

By simulating the above formulas including Z_s, θ_s, ϕ_s, the plunging amplitude caused by medium sea conditions was 1.52 m, the pitching amplitude 1.05° and the rolling amplitude 6°. It is of no significance to analyze the effects of rolling motion on ramp takeoff, due to no control system.

3.2 Effects of plunging motion on ski-jump takeoff

Consider the carrier plunging movement only. The initial phase ω_h was set as 0°, 90°, 180° and 270° to achieve the corresponding maximum sinkage, as shown in Table 1. And the curves of flight altitude are illlustrated in Fig. 3.

Table 1 Comparison of maximum sinkage for different phases of plunging motion

ω_h/(°)	Maximum sinkage/m
0	0.7
90	2.5
180	5.5
270	2.7

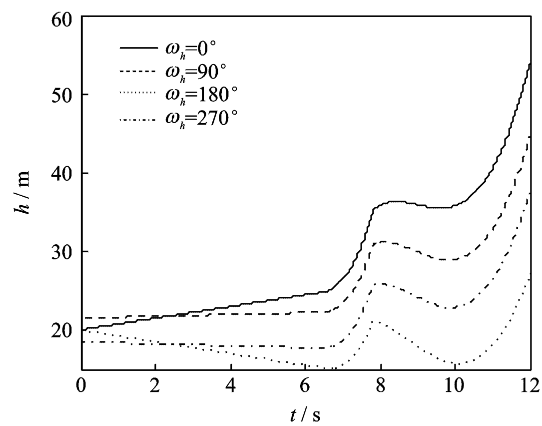


Fig. 3 Flight altitude curves affected by plunging motion

When the initial phase ω_h was 0° and the aircraft was about to leave the vessel, the plunging value was zero, but the rapid was maximum towards the positive direction. And $\omega_h = 90°$ meant the plunging value was maximum towards the positive direction, but the rapid was zero. On the contrary, $\omega_h = 180°$ meant that the plunging value was zero, but the rapid was maximum towards the negative direction. $\omega_h = 270°$ meant that the plunging value was maximum towards the negative direction, but the rapid was zero.

The maximum sinkage followed the change of initial phase. By comparison, the maximum sinkage arrived at the minimum value of 0.7 m when the initial phase was 0°. Meanwhile, the maximum value was 5.5 m when $\omega_h = 180°$. It is fatal that the flight altitude is lower than the height of the horizontal deck. In conclusion, the plunging rate plays a leading role in the effects of plunging motion on ski-jump takeoff. And it is very important to choose an appropriate time for the aircraft to ski-jump takeoff. From the Table 1, it is suggested that the best initial phase ω_h is 0°.

3.3 Effects of pitching motion on ski-jump takeoff

We assumed that the initial phase ω_θ of the pitching motion was 0°, 90°, 180°, and 270°. Consider the ship carrier pitching movement only. We obtained the corresponding maximum sinkage, as shown in Table 2. And Fig. 4 demonstrats the flight altitude during the whole launching process.

Table 2 Comparison of maximum sinkage for different phase of pitching motion

ω_θ/(°)	Maximum sinkage/m
0	0
90	0.2
180	8.2
270	3.8

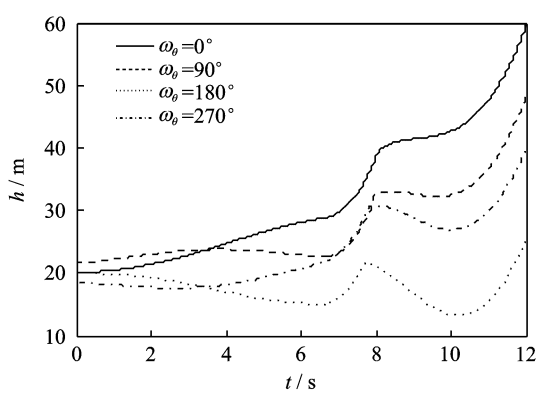


Fig. 4 Flight altitude curves affected by pitching motion

When the initial phase ω_θ of the pitching motion was between 0° and 90°, the value of pitch was positive and the pitch rate decreased gradually from the positive maximum to zero. On this condition, the aircraft had a sinkage close to zero. When the pitch initial phase changed from 90° to 180°, the pitch was positive, meanwhile, the pitch rate decreased gradually from zero to the negative maximum. And when $\omega_\theta = 180°$, the maximum sinkage was 8.2 m, which was not good for takeoff. When the initial phase fell in the area between 180° and 270°, the pitch was negative and the pitch rate increased gradually from the negative maximum to zero, meanwhile, the maximum sinkage decreased correspondingly. When the initial phase located at the area between 270° and 360°, the pitch was negative and the pitch rate increased gradually from zero to the positive maximum. And the aircraft arrived at the maximum value of 3.8 m when the initial phase was 270°.

Fig. 4 shows that the trajectory of aircraft during the horizontal acceleration was similar to the track displacement of the carrier. The vessel was not pitching, while the plane was. And the force the deck imposing on the aircraft had changed, resulting in the change of the speed and the attitude angle. Hence, the maximum sinkage of carrier-based aircraft after leaving the vessel varied.

Table 2 shows that different initial phase caused different sinkage. And when the initial phase of the pitching motion was 0°, the aircraft did not sink after leaving the ship. However, it was dangerous that the maximum sinkage was 8.2 m when $\omega_\theta = 180°$. And it is also fatal that the flight altitude is lower than the height of the horizontal deck. So, in order to launch smoothly for the aircraft and ensure safety of the pilot, it is necessary to choose an appropriate time. And it is suggested to choose a certain value between 0° and 90° as the initial phase of pitching motion.

4 Analysis on Effects of Ship Airwake on Ski-Jump Takeoff

4.1 Ship airwake model

The air around a ship flows unsteadily at a low speed [9], and is significantly affected by the ship's periodic motion[10]. Unfortunately, there is little published data suitable to build a generic model of ship airwake. And no appropriate airwake model has been found. Although there have been a lot preliminary studies on ship airwake models, these models are either insufficient or unavailable, for they are limited within military service. Most researchers focused on helicopter-on-deck scenarios with a very limited area. Nevertheless, The studies of wind flow around buildings can be expanded to the study on airwake around a ship from different directions.

Further, only the model which assures adequate and reliable results can be used, which requires appropriate verification and validation. The leading effect of ship airwake is increasing the speed of the carried aircraft relative to the airflow. So, one of the possible ways to build a simplified airwake model is to employ a common turbulence profile, applying corresponding intensity in the area affected by the airwake. And it is adequate to build an approximation to ship airwake using the position and the altitude of aircraft and the altitude relative to the ship as inputs. It is pointless to simulate the whole three-dimensional airwake. Fig. 5 shows the speed curves of air flow in x and z of the earth-surface inertial reference frame. And the curves are corresponding to the certain relative position and altitude. The curve in Fig. 5 represents the speed of air flow in the axis x and the other one the speed of air flow in the axis z.

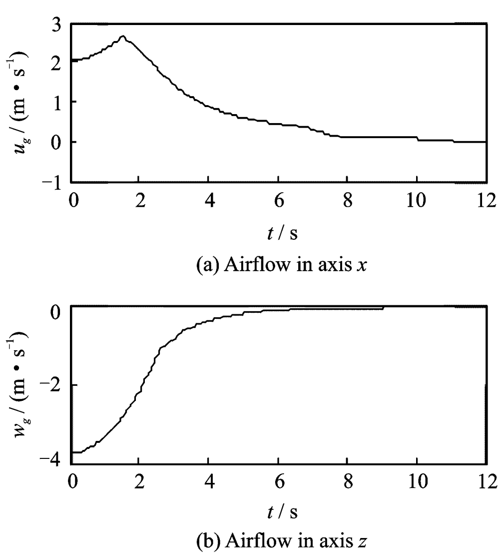


Fig. 5 Speed curves of airwake

4.2 Effects of ship airwake on ski-jump takeoff

The fact that airwake varies with aircraft position and altitude, as well as with time, causes the change of the speed of aircraft relative to the airflow, as shown in Fig. 5. That means the aircraft airspeed has changed. We discussed what kind of impact ship airwake had on ski-jump takeoff without any flight control. Given the elevator preset angle $-5°$ and throttle opening 1, the simulation results are shown in Fig. 6.

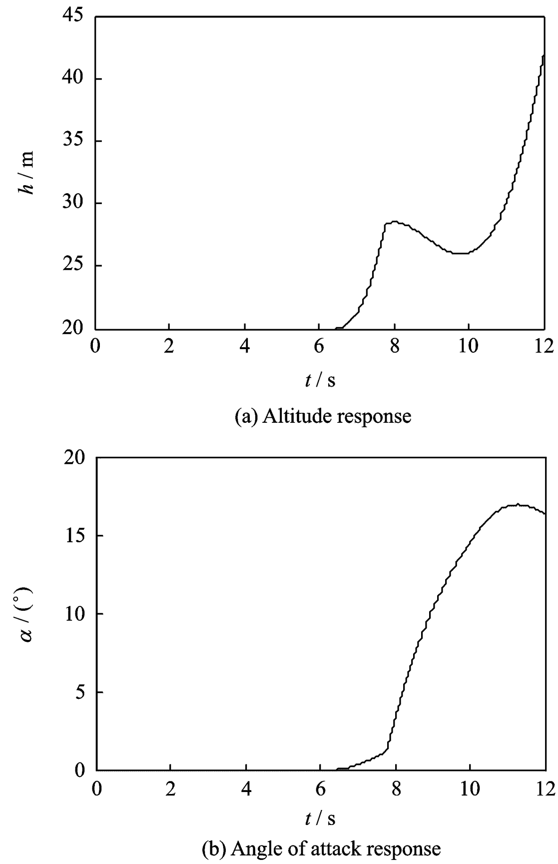


Fig. 6 Simulation curves of launch affected by ship airwake

The benefit of ship airwake is to increase the aircraft airspeed, which causes the rapid increase of the lift force and then the decrease of the sinkage after naval aircraft leaves the carrier. Fig. 6 shows that in the horizontal acceleration, the attack angle did not change, because the lift force was not big enough to balance the weight. And in the whole simulink process, the maximum sinkage after the carried aircraft takeoff was 2.4 m, adequate for launch. Further, the angle of attack was less than the maximum allowable angle of attack. Compared with that in Fig. 2, ship airwake had a small effect on maximum sinkage with, to some extent, reducing the amount of sinking after aircraft takeoff. Nevertheless, airwake doesn't play an effective role in changing the attack angle.

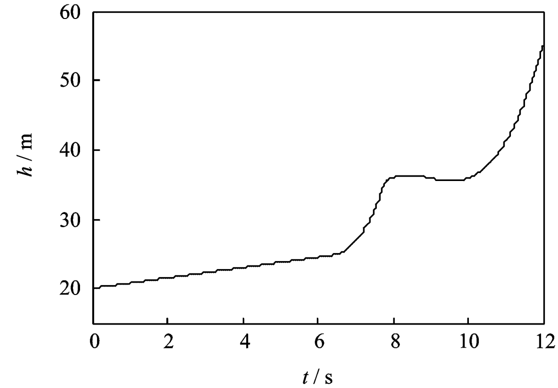
5 Analysis on Effects of Interaction Between Deck Motion and Ship Airwake on Ski-Jump Takeoff

From the analysis in Section 3, we know that various initial phases in the plunging motion cause various maximum sinkages finally and the sinkages differ in the different initial phases in the pitching motion. Hence, in order to reduce the maximum sinkage of carried-based aircraft, it is necessary to choose an appropriate moment, such as the initial phase of 0° in the plunging motion and pitching motion, respectively. And Section 4 also demonstrated that ship airwake plays an effective role in maximum sinkage with, to some extent, reducing the amount of sinking after aircraft takes off.

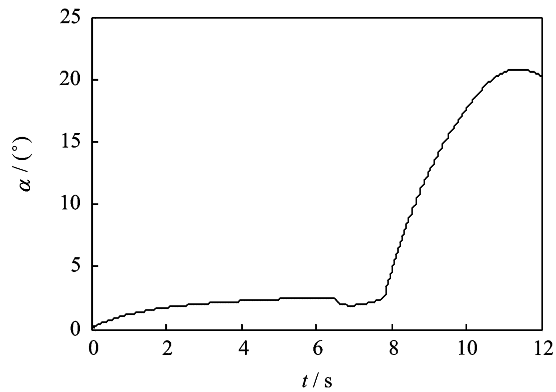
Nevertheless, in order to analyze the effects caused by environmental factors on ski-jump takeoff performance in detail, it is necessary to research the impacts of the interaction between deck motion and ship airwake. Then the effect of the interaction of plunging motion and ship airwake is discussed and so does the effect of the interaction of pitching motion and ship airwake.

5.1 Effects of interaction between plunging motion and ship airwake on ski-jump takeoff performance

Supposing that the ship just does the plunging motion and is disturbed by the airwake, we added the model of the interaction between the plunging motion and ship airwake to the dynamic ramp ski-jump mathematic model. Based on Section 4, it is chosen that the initial phase of plunging motion is 0° in this section. And the effect caused by the interaction is as follows. The simulation curves of ramp-assisted takeoff are shown in Fig. 7.



(a) Altitude response



(b) Angle of attack response

Fig. 7 Simulation curves of launch affected by the interaction of plunging motion and ship airwake

It is obvious that the sinkage of aircraft after leaving the deck was close to zero when the initial phase of plunging motion was 0°. Meanwhile, Fig. 7, demonstrates that the attack angle followed the change of plunging motion during the horizontal and ramp acceleration running stage. Nevertheless, after the aircraft and ship separated, the attack angle increased gradually and the maximum arrived at 21°, which was dangerous for the aircraft. It is necessary to design the feedback control system of attack angle during the air climbing process in the further research. It is concluded that the plunging motion plays a major role in the effects of the interaction between plunging motion and ship airwake on ski-jump takeoff performance.

5.2 Effects of interaction between pitching motion and ship airwake on ski-jump takeoff performance

It was supposed that aircraft was affected by pitching motion and ship airwake on deck. Hence, the model of the interaction between the pitching motion and ship airwake was added to the whole dynamic ramp ski-jump mathematic model. We chose 0° as the initial phase of pitching motion; as described in Section 4. The effect caused by the interaction on launch performance is demonstrated in Fig. 8.

As seen in Fig. 8, the aircraft did not sink

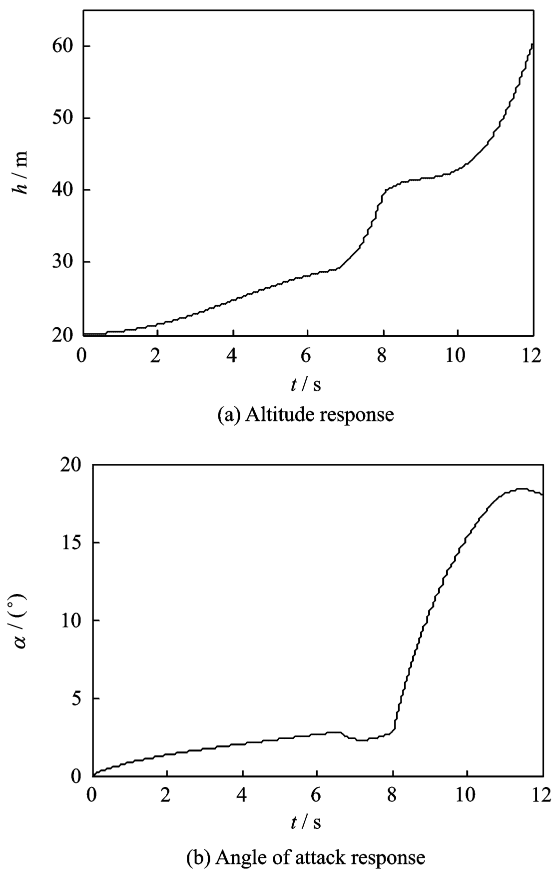


Fig. 8 Simulation curves of launch affected by the interaction of pitching motion and ship airwake

during the air climbing process when the initial phase of pitching motion was 0°. And the attack angle gradually increased in the horizontal acceleration running stage due to the effects caused by the interaction between the pitching motion, and ship airwake and the maximum attack angle was no more than 20°, which was relatively safe. The similar conclusion was also drawn that the pitching motion plays a major role in the effects between the interaction between pitching motion, and ship airwake on ski-jump takeoff performance.

6 Conclusions

We presented a model of deck motion and ship airwake which can be applied to the dynamic ramp ski-jump mathematic model and utilized to simulate and analyze the effects caused by the deck motion with different initial phase and ship airwake separately. We also researched the influence between the interaction of deck motion and ship airwake. We found that it was important to choose an appropriate initial phase with 0° in the plunging motion and a certain value between 0° and 90° in the pitching motion. And ship airwake plays a positive role in reducing the sinkage of aircraft after leaving the deck. By analyzing the effects caused by the interaction between deck motion at medium sea conditions and ship airwake on ramp-assisted takeoff performance, we conduded that the former plays a major role.

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