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Simulation of WIGS Aerodynamic Derivatives in Viscous Flow

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ABSTRACT

Wing in ground effect vehicle is a type of the latest high performance vehicles. Due to the strong nonlinear change of aerodynamics with flight altitude and wind direction always being parallel in wind tunnel, the important aerodynamic derivative to climb angle is hardly to be tested. In this paper, a theoretical method of acquiring partial dynamic derivative of the wing in ground effect vehicle is derived by using the forced vibration of WIG vehicle above a certain flying height. At the same time, the aerodynamic characteristics of WIGS of XTW series are analyzed by means of fluent code using the theoretical method developed. It is shown that the numerical simulation method is reasonable compared with the experimental value, and the theoretical method of acquiring partial dynamic derivative of the wing in ground effect vehicle is feasible.

1 INTRODUCTION

Wing in ground effect vehicle is a new type of ultra high speed ship, whose characteristic properties are familiar to airplane rather than ship. When solving some problems such as the motion stability, maneuverability, agility etc., it is necessary to know the vehicle of its aerodynamic forces and torques, which are often expressed as aerodynamic derivatives. Aerodynamic derivatives can be obtained by theoretical calculation, wind tunnel test or CFD analysis. For aircraft with complex geometry, it is very difficult to calculate the dynamic derivatives by theoretical method, and as while the accuracy of calculation results is difficult to judge.

Normally, the longitudinal stability is the most important characteristics of WIG vehicle. To an aircraft, the parameters determining the longitudinal aerodynamic forces in the wind axis coordinate system usually can be expressed as $(\upsilon, \alpha, \dot{\theta}, \dot{\alpha})$, of which υ means velocity, α means attack angle, $\dot{\theta}$ means pitch angle velocity, while wing in ground effect vehicle's aerodynamic forces show strong nonlinear change to flight height, and the change of pitch angle cause not only variation of attack angle, but also variation of relative position of the vehicle to ground. So the parameters determining the aerodynamic forces of WIGs in the wind axis coordinate system are expressed as $(\upsilon, h, \theta, \alpha, \dot{\theta}, \dot{\alpha})$ and because of $\theta = \alpha + \Theta$,it can be written as $(\upsilon, h, \theta, \Theta, \dot{\theta}, \dot{\Theta})$ instead, of which hmeans flight height, Θ means climb angle, $\dot{\Theta}$ means the velocity of climb angle. As studying problem of WIG vehicle's longitudinal stability, aerodynamic derivatives of lift or drag or moment of pitch coefficient to H and θ can be acquired through wind tunnel test, aerodynamic derivatives due to $\dot{\theta}$ can be get by the same method of aerotechnics, and because of the small change of velocity to WIG vehicle, aerodynamic derivative due to υ is ignored currently. But aerodynamic derivatives of lift or drag or moment of pitch coefficient to Θ and $\dot{\Theta}$ are hardly to be acquired by conventional wind tunnel test, therefore CFD methods are investigated in this paper to make the problem settled. The relationship of angles of pitch, attack and climb is showed in figure1.

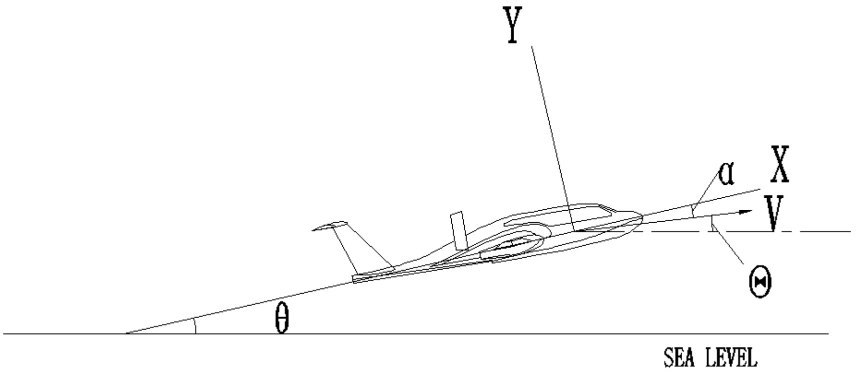

Fig 1: Relationship of different attitude angles

In the field of aviation, many CFD methods have been developed to obtain the aerodynamic coefficients of forces, Ye Chuan and Ma Dongli[1] using the sliding mesh technique to simulate the forced pitch oscillation，and the sum of pitching moment angle of attack rate derivative and pitch rate derivative was obtained. At the same time the rotating reference flame was used to gain the pitching moment pitch rate derivative by simulating the steady climb movement． So the pitching moment angle of attack rate derivative and pitch rate derivative can be obtained separately after the above two steps. While Huang Longtai etc.[2] set up forced vibration model of the airship in the atmosphere based on unstructured dynamic mesh method, and through solving N-S equations with the finite volume method, to figure out the airship's dynamic derivatives on basis of numerical simulation. According to the investigation of ZHU Haitao, BAI Wen[3], time averaged aerodynamic force coefficients, static derivative and dynamic derivative for full aircraft configuration TCR model at attack angle of 0°~30° were computed through unsteady CFD method with moving mesh in order to investigate the capability of the method to complex geometries.

In the field of grid technology, since 1980s Formaggia[5] developed grid remeshing technique and Batina[4] developed grid deforming technique, unstructured dynamic mesh methods have made great progress in complicated model's unsteady simulation of flow.

In this paper, the basic hypothesis and solution principles are deduced to obtain the dynamic derivatives of lift or drag or moment of pitch coefficient to Θ by simulation of the forced heave oscillation. Based on the simulation of the latest XTW series WIG craft making heave oscillation over moving ground by CFD method, some crucial dynamic derivatives are calculated. Before this work, aerodynamic coefficient of the latest WIG craft was calculated by means of CFD method, and the results are compared with wind tunnel test datum to make sure that the aerodynamic derivative calculation method is effective and feasible.

2 SOLVING METHOD OF DYNAMIC DERIVATIVE C_y^{Θ}、C_x^{Θ} AND M_z^{Θ}

The characteristic of the dynamic derivative is that if the specific parameter such as the climb angle changes while other parameters keep constant, the motion of WIG vehicle will be unsteady rather than steady. Due to formula $C_y^{\Theta} = C_y^{\dot{h}}\cos\Theta$, derivative of aerodynamic forces to climb angle is aerodynamic forces to the vertical velocity actually, so dynamic derivatives of WIG vehicle in longitudinal motion mainly concerned in engineer is mainly composed of $C_y^{\Theta}, C_x^{\Theta}, M_z^{\Theta}, M_z^{\dot{\theta}}, M_z^{\dot{\Theta}}$.

To study the dynamic derivative of climb angle of WIG vehicle, we make the following setting: The heave oscillation is made over the flight height and the motion describe as follows:

$$\begin{cases} h = h_0 + \Delta h = h_0 + a(1 - \cos\omega t) \\ \qquad \omega = \text{const} \\ \quad \theta = \theta_0 = \text{const} \end{cases} \tag{1}$$

Where a indicate amplitude of heave oscillation, ω indicate frequency of oscillation. The inlet velocity are steady and parallel to the baseline of WIG vehicle, so the force balance equation in translational coordinate system can be as follows：

$$L(t) = \frac{1}{2}\rho\upsilon^2 S C_{yg}(h, \Theta, \dot{\Theta}) \tag{2}$$

where L indicate lift, ρ is density of air, S is calculating area of vehicle, C_{yg} is aerodynamic coefficient of lift. Calculating the derivative of the equation above with t, then

$$\frac{dL(t)}{dt} = \rho S\upsilon\frac{d\upsilon}{dt}C_{yg} + \frac{1}{2}\rho\upsilon^2 S\left(C_{yg}^{h}\frac{dh}{dt} + C_{yg}^{\Theta}\frac{d\Theta}{dt} + C_{yg}^{\dot{\Theta}}\frac{d\dot{\Theta}}{dt}\right) \tag{3}$$

For $h = h_0 + a(1 - \cos\omega t)$

$$\frac{dh}{dt} = \upsilon_0 \mathrm{tg}\Theta = a\omega\sin\omega t \tag{4}$$

$$\upsilon = \upsilon_0\sec\Theta \tag{5}$$

$$\frac{d\upsilon}{dt} = \upsilon_0\sec\Theta\,\mathrm{tg}\Theta\frac{d\Theta}{dt} \tag{6}$$

$$\frac{d\Theta}{dt} = \frac{a\omega^2}{\upsilon_0\sec^2\Theta}\cos\omega t \tag{7}$$

$$\frac{d\dot{\Theta}}{dt} = \frac{-2l\sin\Theta\cos^3\Theta a^2\omega^4}{\upsilon_0^3}\cos^2\omega t - \frac{l\cos^2\Theta a\omega^3}{\upsilon_0^2}\sin\omega t \tag{8}$$

Where l is characteristic length.

Distinctively, at $\omega t = 2n\pi$, according to equations above， the dynamic derivative can be deduced as follows at equilibrium point $(\upsilon_0, h_0, \theta_0, \Theta = 0)$, where subscript "0" means the value at equilibrium point：

$$C_{yg0}^{\Theta} = \left.\frac{\upsilon_0 L'(2n\pi/\omega)}{a\omega^2}\right/\frac{1}{2}\rho\upsilon_0^2 S \tag{9}$$

In a similar way, the dynamic derivative of drag and pitch moment to climb angle is deduced as follows,

$$C_{xg0}^{\Theta} = \left.\frac{\upsilon_0 D'(2n\pi/\omega)}{a\omega^2}\right/\frac{1}{2}\rho\upsilon_0^2 S \tag{10}$$

$$M_{z0}^{\Theta} = \left.\frac{\upsilon_0 M'(2n\pi/\omega)}{a\omega^2}\right/\frac{1}{2}\rho\upsilon_0^2 Sl \tag{11}$$

Typical calculation results of L(t)、D(t)、M(t) and Δh change with time that can be expressed as figure 2, so $L'(2n\pi/\omega)$、 $D'\left(2n\pi/\omega\right)$and $M'\left(2n\pi/\omega\right)$could be solved accurately by means of figure2. Where D means drag, M means pitch moment, and at the same time, $C_y^{\Theta}, C_x^{\Theta}, M_z^{\Theta}$ in wind axes can be solved conveniently.

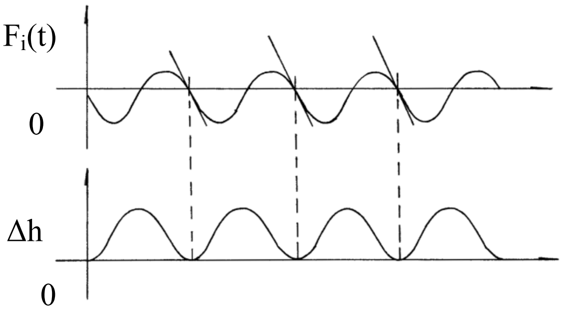

Fig 2: Numerical calculation of force and torque wave form

3 NUMERICAL SIMULATION OF WIG VEHICLE USING CFD SOFTWARE FLUENT

3.1 Description of objects simulated

In this paper, the latest designing scheme of XTW series is adopted to investigating the aerodynamic performance by means of CFD methods. The vehicle and its units are composed of pair of ground effect wings and side wings, two out stretched vertical tails, high installing horizontal tail, and hull with double-step glider, a pair of side boat, overall outline showed in figure 3.

Fig 3: The WIGS shape of CFD investigated

Fig 4: The WIG vehicle of XTW-4 in trial

3.2 Numerical computation method

The flow is assumed to be viscous flow, then three-dimensional transient Navier-Stokes equation in tensor forms can be expressed[7][9]:

$$\frac{\partial(\rho u_i)}{\partial t}=-\frac{\partial(\rho u_i u_j)}{\partial x_j}-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]+F_i \tag{12}$$

and equation of continuity [7][9]:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u_i)}{\partial x_i}=0 \tag{13}$$

Where $u_{i,j}$ represent velocity tensor. At first, the method of static derivatives calculation of the latest XTW series WIG craft with the CFD code FLUENT is investigated, where the RANS approach and the algorithm SIMPLE are applied. The model of WIG craft that been calculated is full scale and the calculation domain of flow field is composed of 8 times model lengths in longitudinal direction and 4 times model extents wide. The computational domain is meshed with unstructured cells. The mesh around the model is shown in Figure 3.Total cells number is about 1.17 million.

The boundary condition and initial condition are set as follows: inlet velocity is 34m/s, the no-slip condition has been applied to the model and the moving ground walls. Wall functions were used as a bridge between the viscosity affected regions near the solid walls and the fully turbulent regions.

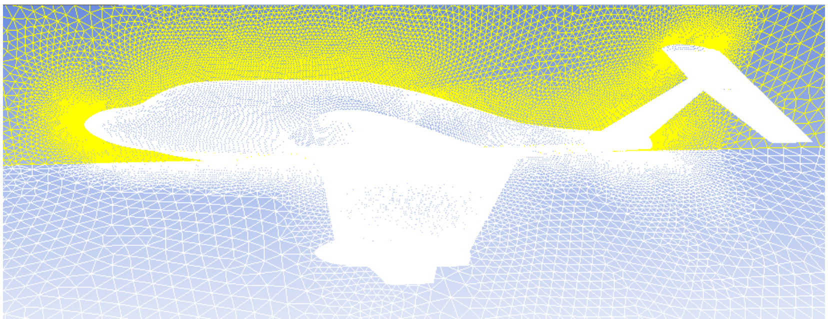

Fig 5: The computational domain near the model

By comparison of calculation results with experiment data(fig.4), the difference between them is not more than 4%， and it is proved that the sst-kω turbulence model is applicable and the grid scale is suitable.

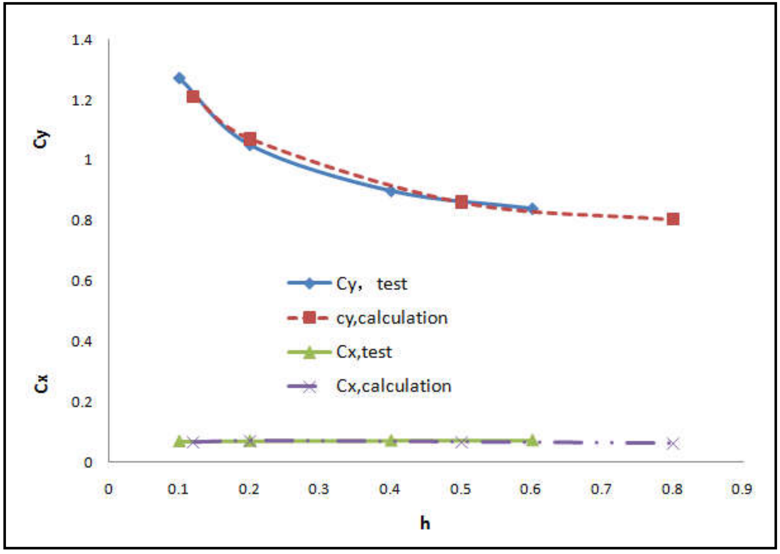

Fig 6: The comparison of lift and drag coefficient

Then the same technique is applied on the simulation of dynamic derivatives, while the craft make heave oscillation over moving ground.

Heave oscillation of WIG vehicle is expressed with formula (1), while the amplitude of heave oscillation is set with 0.5m, and frequency is 1.0rad/s, this is mainly concerning of engineering practice.

In fluent code, the motion of heave oscillation is read as user defined file. Because the lift and the drag of model in flow show periodical change according to the heave oscillation, it can be fitted with curve of sine function, therefore it is convenient to extract the aerodynamic derivatives.

4 RESULTS OF NUMERICAL SIMULATION OF HEAVE OSCILLATION

4.1 Performance analysis of lift and drag

The CFD simulation result of lift coefficient of WIG vehicle clearly support the traditional theory, when flight height declines, the lift get gradually increasing, it is because that the ground effect is strengthened. The lifts produced by different aerodynamic component are shown in table 1. Among all aerodynamic components, the main wing and boat are most heavily affected by ground effect, the lifts increase 37% and 48.8% respectively from the crest of flight to the valley. And it is clear that the main wing constitute the major lifting component for the model configuration in determining the overall aerodynamic performance, its lift make up 68% to 65% proportion of the total number changing according to flight height. The lifts of boat change from 15% proportion of the total number at the valley of flight height and decease to 13% at the crest of flight height. From table 1,it can be observed that the lifts of high mounted horizontal tail distinctly raised when the flight height deceased, this phenomenon can be explained as that downwash flow caused by lift of main wing in ground effect is restricted so that attack angle of the flow around tail increase. Other components such as side wing, side boat and vertical tail also make some change, but have little influence on total lifts.

Table1. Lifts variation caused by oscillations in flight altitude

Aerodynamic component	**Lifts**	
	At crest of flight height （N)	**At valley of flight height （N)**
Horizontal tail	2606.9	3247.7
Boat	3092.3	4600.4
Main wing	14832.0	20284.5
Side boat	394.6	255.1
Side wing	1889.6	1970.1
Vertical tail	-212.1	-136.7
Total	22603.2	30221.2

The drags of the vehicle appear no significant changes, and show approximately deceasing 8% of total (fig 2). The main reason should be that downwash flow of the model is restricted so that induced drag reduced.

Table2. Drag variation caused by oscillations in flight altitude

Aerodynamic component	**Drags**	
	At crest of flight height （N)	**At valley of flight height （N)**
Horizontal tail	320.6	313.8
Boat	403.8	381.5
Main wing	979.1	878.5
Side boat	99.5	76.8
Side wing	96.7	85.0
Vertical tail	65.8	72.4
Total	1965.5	1808.0

4.2 Analysis of flow field characteristics

Pressure distribution of the vehicle on the upper surface and lower surface at different flight height are shown from figure 7 to figure 10, by comparison it can be proved that the pressure distribution of vehicle on the upper surface had no obvious change whether at crest of flight or at valley, but it is significantly different when concerning with the lower surface of the vehicle. The maximum dynamic pressure of the vehicle on the lower surface increase approximately about 57% as flight height changed from valley to crest, so it is proven that the reason of lifts of the craft obviously increasing can be attributed to the change of dynamic pressure on the lower surface.

There are obvious low-speed zone at bow, stern and step of bottom in fig. 11 and fig.12, and the velocity of flow between vehicle and ground gradually decease according to the clearance diminishing. And there is obvious detached eddy at the stern.

According to fig. 13 and fig.14, the dynamic pressure of flow between vehicle and ground has distinct change at different clearance.

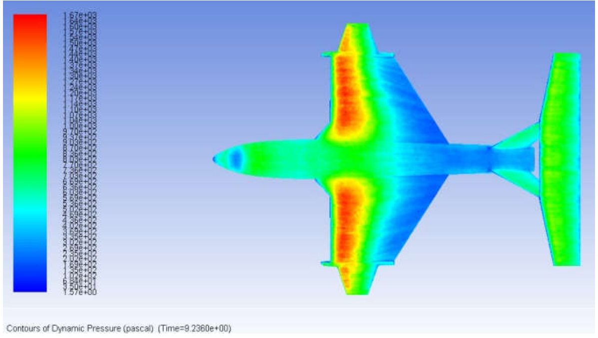

Fig 7: Pressure distribution of upper surface at the crest of flight height oscillating

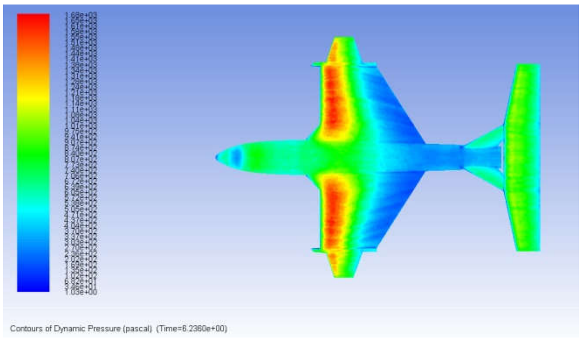

Fig 8: Pressure distribution of upper surface at the bottom of flight height oscillating

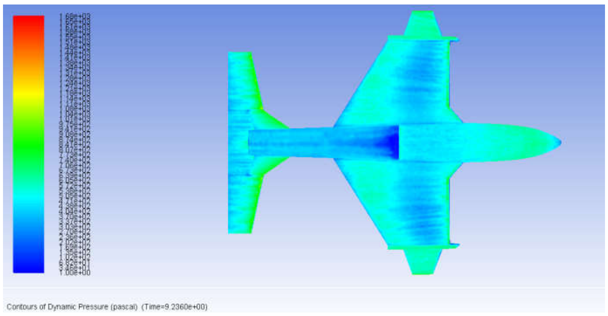

Fig 9: Pressure distribution of lower surface at the crest of flight height oscillating

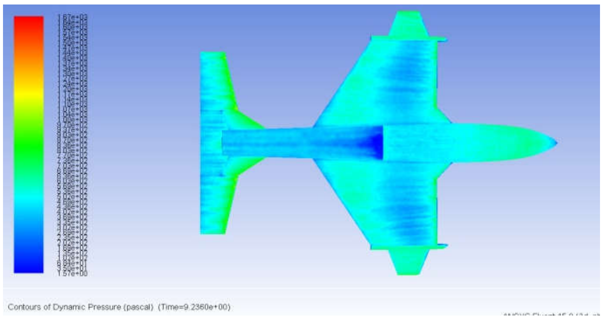

Fig 10: Pressure distribution of lower surface at the bottom of flight height oscillating

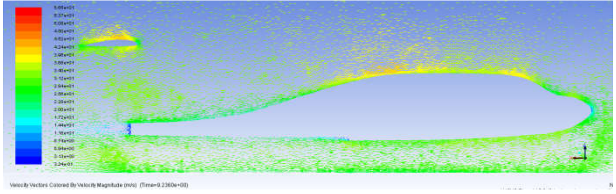

Fig 11: Velocity vector distribution of symmetrical plane at the crest of flight height oscillating

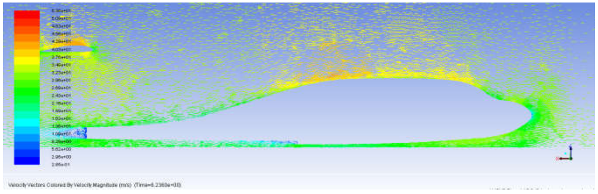

Fig 12: Velocity vector distribution of symmetrical plane at the bottom of flight height oscillating

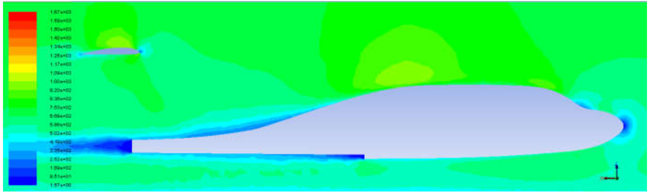

Fig 13: Pressure distribution of symmetrical plane at the crest of flight height oscillating

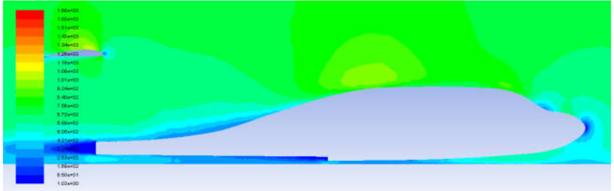

Fig 14: Pressure distribution of symmetrical plane at the bottom of flight height oscillating

4.3 analysis of aerodynamic force oscillation

The lifts, drags and moments of vehicle show periodic oscillating according to forced oscillation of flight height, shown as fig.15 to fig.17, and each of them can be fitted with sinusoid.

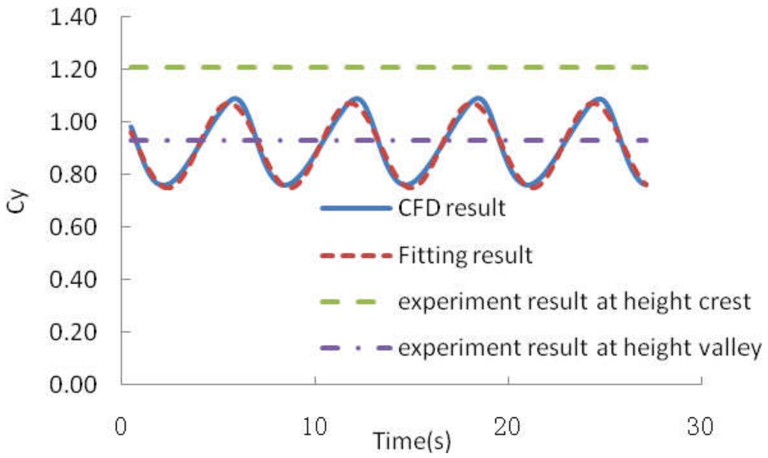

Fig 15: The variation of WIGS lift during forced oscillations

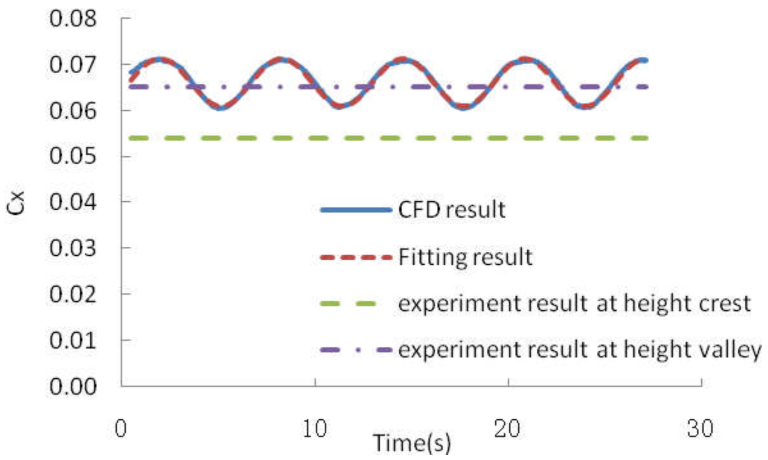

Fig 16: The variation of WIGS drag during forced oscillations

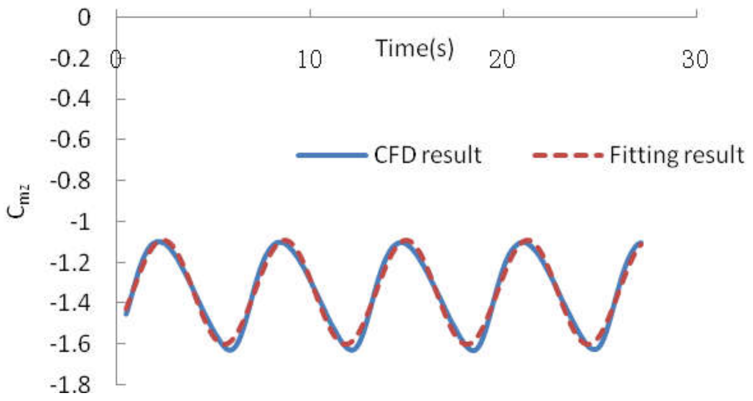

Fig 17: The variation of WIGS pitch moment during forced oscillations

Utilizing oscillation curves and formula (9) ~ (11) deduced, dynamic derivatives to climb angle can be calculated：

$$C_{yg0}^{\Theta}=\frac{\upsilon_0 L'(2n\pi/\omega)}{a\omega^2}\Big/\frac{1}{2}\rho\upsilon_0^2 S=-7.46$$

$$C_{xg0}^{\Theta}=\frac{\upsilon_0 D'(2n\pi/\omega)}{a\omega^2}\Big/\frac{1}{2}\rho\upsilon_0^2 S=0.328$$

$$M_{z0}^{\Theta}=\frac{\upsilon_0 M'(2n\pi/\omega)}{a\omega^2}\Big/\frac{1}{2}\rho\upsilon_0^2 Sl=2.36$$

5 CONCLUSION

Investigation of aerodynamic derivatives of wing in ground effect vehicle in non-steady flow is significantly complicated whether in method of physical experiment or in technique of test data processing, at the same time, it is hardly to assure the accuracy of test data because of the influence of system damping and simulation of movement inertia. For the study of aerodynamic derivatives of wing in ground effect vehicle in non-steady flow by means of CFD method is seldom reported so far in China, in this paper we present a new method to solve this kind of aerodynamic derivatives by forced heave oscillation, and through the numerical simulation, dynamic derivatives of forces to climb angle are calculated, the conclusion can be reached as follows:

The theoretical method deduced to acquire aerodynamic derivatives of lift, drag and moment to climb angle are rational, and can be utilized in CFD simulation. At the same time, through the simulation result, it shows the correct rules that lift increase and drag decrease if clearance between the vehicle and ground get larger, just as wind tunnel test. Results of aerodynamic coefficient of simulation differ with test data of about 10%~18%. The main reason is that the test data in this paper are experiment in steady flow, but the numerical simulation is put forward in unsteady flow, and there are influences of uncertainty in test and calculation error. To sum up, the method put forward in this paper is rational and effective, and the result can be used to guiding the design of product.

The method put forward in this paper to investigate aerodynamic derivatives of lift, drag and moment to climb angle is very simple and efficient, based on this method, aerodynamic derivatives of lift, drag and moment to climb angular velocity can also been developed.

It is possible to get aerodynamic derivatives of forces to pitch angular velocity separated from aerodynamic derivatives of forces to climb angular velocity by using the method put forward in this paper, it is very important and constructive to study the influence of different aerodynamic parameter in isolation.

According to the complicated object studied in this paper, numerical calculation show good convergence.

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