SIMULATION METHOD FOR WIND TUNNEL BASED VIRTUAL FLIGHT TESTING

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The Wind Tunnel Based Virtual Flight Testing (WTBVFT) could replicate the actual free flight and explore the aerodynamics/flight dynamics nonlinear coupling mechanism during the maneuver in the wind tunnel. The basic WTBVFT concept is to mount the test model on a specialized support system which allows for the model freely rotational motion, and the aerodynamic loading and motion parameters are measured simultaneously during the model motion. The simulations of the 3-DOF pitching motion of a typical missile in the vertical plane are performed with the open-loop and closed-loop control methods. The objective is to analyze the effect of the main differences between the WTBVFT and the actual free flight, and study the simulation method for the WTBVFT. Preliminary simulation analyses have been conducted with positive results. These results indicate that the WTBVFT that uses closed-loop autopilot control method with the pitch angular rate feedback signal is able to replicate the actual free flight behavior within acceptable differences.

Keywords: WTBVFT; free flight; simulation method; closed-loop control.

1. Introduction

Modern high-performance fighter aircraft and missile are being designed with maneuverability as a high priority. Extreme multiple-axis maneuvers, which are characterized by high angles of attack and large angular rotation rates, typically require that the vehicle operate in the post-stall regime of the lifting surfaces. During these maneuvers, the rapid change of the motion parameters, such as attitude, angular rate, angular acceleration will induce the strong unsteady characteristic of the flow around the vehicle, and the dynamic and time-dependent effects of the nonlinear flow characteristics, including flow separation, vortex shedding, and vortex lag effects, contribute significantly to the behavior and maneuvering capability of the vehicle. The presence of the unsteady vortex wake introduces memory into the flow problem, and the nonlinear forces and moments on the vehicle depend on the time history of the motion and the wake development. The aerodynamic forces and moments will be strong nonlinear with the characteristic of the hysteresis, catastrophe and bifurcation, and not only depend on the vehicle attitude, but also strongly depends on the time history, amplitude and frequency of the motion. The nonlinear change of the aerodynamic forces and moments will induce the rapid change of motion parameters of the vehicle. Consequently, there are strong nonlinear coupling between the motion parameters and the aerodynamic parameters¹.

The traditional test techniques, such as steady test, small and large amplitude forced oscillation test, rotary balance test and so on, are based on the linear superposition principle, and hard to effectively simulate and research the actual free flight maneuver. There is need to develop a new wind tunnel test technique that is able to replicate the actual free flight. The Wind Tunnel Based Virtual Flight Testing (WTBVFT)^{2, 3} can provide this capability. The basic WTBVFT concept is to mount the test model on a specialized wind tunnel support system which allows for the model rotational motion to achieve realistically simulate the actual free flight. The test model will be able to freely experience all three degree-of-freedom rotational motion, the control surfaces will be able to be real time control according to the flight control systems demand, and the aerodynamic loading and motion parameters are measured simultaneously during the test. The WTBVFT will be able to test the response and the control characters of the vehicle, achieve the aim of integrated research on the aerodynamics and flight dynamics, and explore the aerodynamics/flight dynamics nonlinear coupling mechanism. To develop the WTBVFT, the simulation method is one of the key theoretical problems that must be firstly resolved.

The current paper aims to investigate the simulation method for the WTBVFT. The simulations of the three degree-of-freedom (3-DOF) pitching motion of a typical missile in the vertical plane are performed with the open-loop and closed-loop control methods. The main differences between the WTBVFT and the actual free flight, and its effect are analyzed. Finally, the simulation method for the WTBVFT is studied.

2. Effect of Main Differences between the WTBVFT and Actual Free Flight

2.1. Main difference

Generally, a rigid body is able to experience motions with six degree-of-freedom in the actual free flight. They are three translational motions of the centre of gravity and three rotational motions about the centre of gravity. During the actual free flight, the speed may change rapidly, and results in rapid changes of the Mach number and Reynolds number. The velocity direction is able to be determined by the flight path angle γ and the heading angle χ , and the flight path angle is effect on the flight altitude. When the flight path angle is not zero, or changes during flight, the flight altitude will be change.

In the WTBVFT, the airflow speed generally does not change during the test, and the Mach number and Reynolds number is nearly constant. Since the centre of gravity of the test model is fixed, the linear displacement is constrained and the model does not allow the translational motions, and will be only able to freely experience rotational motions about the three body axes. So the velocity direction is not able to change and the flight path angle is always zero due to the constrained linear displacement.

Therefore, there are two main differences between the WTBVFT and the actual free flight: the constrained linear displacement and the change of the speed.

2.2. Effect of the main differences

A three degree-of-freedom (3-DOF) pitching motion in the vertical plane for a typical missile is simulated to analyze the effect of the main differences.

2.2.1. Modeling of the missile longitudinal dynamics

Fig. 1 shows the 3-DOF pitching motion in the vertical plane $Ox_g z_g$. The motion refers to two coordinate systems. They are the inertial axes system $Ox_g y_g z_g$ that is fixed to the earth and the body axes system $Ox_b y_b z_b$ that is fixed to the missile centre of gravity. The motion involves the two translational motions in the Ox_g and Oz_g directions and the rotational motion about the Oy_g producing change in the Euler pitch angle θ .

Fig. 1. The 3-DOF pitching motion in the vertical plane $Ox_g z_g$

The equations of the 3-DOF pitching motion⁴ for the actual free flight and the 1-DOF pitching motion due to the constrained linear displacement for the WTBVFT are:

$$\begin{cases} \dot{V} = \frac{Z_b \sin \alpha - (T + X_b) \cos \alpha}{m} + g \sin(\theta - \alpha) \\ \dot{\alpha} = \frac{Z_b \cos \alpha - (T + X_b) \sin \alpha}{mV} + g \cos(\theta - \alpha) + q \\ \dot{q} = \frac{M_y}{I_y} \\ \dot{\theta} = q \\ \dot{x}_g = V \cos(\theta - \alpha) \\ \dot{z}_g = -V \sin(\theta - \alpha) \end{cases} \quad \begin{cases} \dot{\alpha} = q \\ \dot{q} = \frac{M_y}{I_y} \\ \dot{\theta} = \alpha \end{cases} \quad (1)$$

2.2.2. Aerodynamic modeling of the missile

Mathematic modeling for the missile aerodynamics accord to wind tunnel test results⁵:

$$\begin{aligned} C_x &= C_x(M, \alpha, \delta_z) = \frac{X_b}{0.5 \rho_\infty V_\infty^2 S} = \sum_{j=1}^4 s_{1j} \delta_z^{j-1} \\ C_z &= C_z(M, \alpha, \delta_z) = \frac{Z_b}{0.5 \rho_\infty V_\infty^2 S} = \sum_{j=1}^4 s_{2j} \delta_z^{j-1} \\ C_m &= C_m(M, \alpha, q, \delta_z) = \frac{M_y}{0.5 \rho_\infty V_\infty^2 S l} = \sum_{j=1}^4 s_{3j} \delta_z^{j-1} + C_{mq} \frac{ql}{2V_\infty} \\ s_{ij} &= s_{ij}(M, \alpha) \quad i = 1, 2, 3; j = 1, 2, 3, 4 \end{aligned} \quad (2)$$

2.2.3. Analysis of the missile open-loop simulations

Given the control surfaces deflection angle: $\delta_z(t) = -10^\circ, t \geq 0$. Fig. 2 shows the angle of attack, pitch angular speed, and Mach number history of the missile open-loop simulations. Three simulations that involve the 3-DOF (red dashed line) and 1-DOF (blue line) motion with constant speed, and the 1-DOF motion (green dash dotted line) with variable speed are performed.

(1)Effect of the constrained linear displacement

Compared the 3-DOF motion with the 1-DOF motion with constant speed, there are significant differences between the two simulations. Note that the amplitude of the 1-DOF motion is larger than the 3-DOF motion, the frequency of the 1-DOF motion is higher than the 3-DOF motion, and the differences between the two simulations increase in time. The reason for these differences is that the 3-DOF is able to experience the translational motions, and the flight path angle continuously changes during the flight, but in the 1-DOF motion, the flight path angle is always zero and unchangeable due to the constrained linear displacement.

Therefore, the linear displacement has a significant impact on the angle of attack and pitch angular rate history, and subsequently, its aerodynamic forces and moments.

Fig. 2. Results of the open-loop simulations.

(2) Effect of the change of the speed

Comparing the two 1-DOF motion with constant and variable speeds, there are also significant differences between the two simulations. Note that the amplitude of the motion with constant speed is smaller than the motion with variable speed, and the frequency is higher than the motion with variable speed. The reason for these differences is that an additional increment of the pitch moment is produced due to the change of the speed, and leads to the differences of the pitch moment, and subsequently, the angle of attack and pitch angular rate history between the two simulations.

The above simulations show that the constrained linear displacement and the change of the speed can lead to the significant differences between the 1-DOF motion and the 3-DOF motion, and have a significant impact on the angle of attack and pitch angular rate history, and subsequently, aerodynamic forces and moments.

Therefore, the effect of the constrained linear displacement and the change of speed need to be corrected in the WTBVFT. Since the speed is unable to rapidly change in the wind tunnel, the correction of the effect of the constrained linear displacement in the WTBVFT should be focused on to achieve to replicate the actual free flight.

3. Analysis of the Simulation Method for the WTBVFT

The results of the missile open-loop simulations show that there are significant differences between the WTBVFT and the actual free flight due to the constrained linear displacement, and the WTBVFT is not able to replicate the actual free flight. So the WTBVFT cannot use the open-loop control method.

The simulations of the closed-loop control with a typical three-loop autopilot are performed⁶. The normal acceleration is sensed by the accelerometer, and the body angular rate that feedback to the autopilot is sensed by the rate gyro during the flight. In the actual free flight, the pitch angular rate is measured by the rate gyro and feedback to the autopilot. In the WTBVFT, due to the constrained linear displacement, the flight path angle is always zero, and therefore, only the angle of attack rate is measured by the rate gyro and feedback to the autopilot.

For the WTBVFT, there are two options of the angular rate feedback. One approach is to feedback directly the angle of attack rate as measured by the rate gyro (Fig. 3). The second approach is to use reconstructed pitch angular rate q as the feedback signal (Fig. 4). In the first approach, there is no need to reconstruct the signal, but there is a difference with the feedback signal of the actual free flight. In the second approach, there is need to combine the angle of attack rate measured by the rate gyro with the simulation estimate of the change of the flight path rate due to the translational motion.

Given the commanded normal acceleration:

$$n_{zc}(t) = \begin{cases} -15g, & 0 \leq t \leq 1 \\ 10g, & 1 \leq t \leq 2 \\ 5g, & 2 \leq t \leq 3 \\ -10g, & 3 \leq t \leq 5 \end{cases} \quad (3)$$

Four simulations (Fig. 5) that involve the 3-DOF motion with constant (red dashed line) and variable (brown dashed line) speed, the 1-DOF motion with constant speed using $\dot{\alpha}$ (green line) and q (blue line) feedback signal are performed. The 3-DOF motion simulates the actual flight and the 1-DOF motion simulates the WTBVFT.

3.1. Constant speed

3.1.1. Angle of attack rate feedback signal

Note that there is a difference in constant speed state response between the actual free flight and the WTBVFT simulations. The reason for the difference is that the total pitch angular rate $\dot{\theta} = \dot{\alpha} + \dot{\gamma}$ is feedback to the autopilot in the free flight, but only the angle of attack rate $\dot{\alpha}$ is feedback to the autopilot in the WTBVFT.

During a steady maneuver, the pitch moment goes to zero when missile eventually trims at a given angle of attack and its angle of attack rate vanishes: $\dot{\alpha} = 0$. However, since the missile is maneuvering, its pitch angular rate does not vanish in the actual free flight because it is the sum of the angle of attack rate and the flight path angle rate which is clearly non-zero. In the WTBVFT, since the test model flight path angle is always zero and never changes due to the constrained linear displacement, the pitch angular rate is always equal to the angle of attack rate and goes to zero: $q = \dot{\alpha} = 0$.

At trim, the pitch moment equation is:

$$C_m = \sum_{j=1}^4 s_{3j} \delta_z^{j-1} + C_{mq} \frac{ql}{2V_\infty} = 0 \tag{4}$$

In the actual free flight, the last term is non-zero, but becomes zero in the WTBVFT. Therefore, to achieve equilibrium, the free flight missile and the WTBVFT test model set the elevator at different deflections, resulting in difference trim angles of attack, as shown in Figs. 5(c) and (d).

Fig. 3. Block diagram for the three-loop autopilot using angle of attack rate feedback.

Fig. 4. Block diagram for the three-loop autopilot using pitch angular rate feedback.

3.1.2. Pitch angular rate feedback signal

As shown in Fig. 5, when the pitch angular rate is feedback to the autopilot, the normal acceleration, angle of attack, elevator deflection, pitch angular rate histories, and computed trajectory of the 1-DOF and 3-DOF motion with constant speed are nearly identical. It is shown that by using the pitch angular rate feedback signal, the WTBVFT is able to replicate the actual free flight with constant speed.

3.2. Variable speed

When the speed is variable in the actual free flight, there are some differences between the 3-DOF motion with variable speed and the 1-DOF motion using the pitch angular rate feedback signal with constant speed. The reason is that for the free flight simulations, as the speed continuously decreases (Fig. 5 (b)), the angle of attack must continue to increase to achieve the commanded normal acceleration. To achieve this, the control surfaces must continue to deflect. Eventually, the speed decreases sufficiently that the control surfaces reach their limit and can go no further. At that point, the angle of attack stops increasing.

Since the Mach number in the wind tunnel is nearly constant, the WTBVFT simulations maintain the commanded normal acceleration without a problem. Fig. 5 (b) shows that the Mach number of free flight goes through rapid changes in several seconds. This may not be possible for the most wind tunnels which require significantly more time to achieve desired airflow Mach number conditions. These result in some differences for the angle of attack and the elevator deflection histories.

It should be noted that even though there are significant difference in the Mach number, the WTBVFT and the actual free flight simulations do show a great deal of similarity throughout the flight.

(a) Normal acceleration history

(b) Mach number history

(c) Angle of attack history

(d) Elevator deflection history

(e) Pitch angular rate history

(f) Trajectory

Fig. 5. Results of the closed-loop simulations using angle of attack rate and pitch angular rate feedback.

4. Conclusions

From the analysis above, we can draw some conclusions:

- (i) There are two main significant differences between the WTBVFT and the actual free flight: the constrained linear displacement and the change of speed. The correction of the effect of the constrained linear displacement in the WTBVFT should be focused on to achieve to replicate the actual free flight.
- (ii) The results of the missile open-loop simulations show that there are significant differences between the WTBVFT and the actual free flight, and the WTBVFT is not able to replicate the actual free flight. So the WTBVFT cannot use the open-loop control method.
- (iii) For closed-loop control systems using a typical three-loop autopilot, the WTBVFT that uses the pitch angular rate feedback signal is able to compensate for the effect of the constrained linear displacement, and achieve to replicate the actual free flight behavior within acceptable differences. As expected, due to the unchangeable speed in the WTBVFT, some discrepancies were noted.

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