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Initial virtual flight test for a dynamically similar aircraft model with control augmentation system

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Abstract To satisfy the validation requirements of flight control law for advanced aircraft, a wind tunnel based virtual flight testing has been implemented in a low speed wind tunnel. A 3-degree-of-freedom gimbal, ventrally installed in the model, was used in conjunction with an actively controlled dynamically similar model of aircraft, which was equipped with the inertial measurement unit, attitude and heading reference system, embedded computer and servo-actuators. The model, which could be rotated around its center of gravity freely by the aerodynamic moments, together with the flow field, operator and real time control system made up the closed-loop testing circuit. The model is statically unstable in longitudinal direction, and it can fly stably in wind tunnel with the function of control augmentation of the flight control laws. The experimental results indicate that the model responds well to the operator's instructions. The response of the model in the tests shows reasonable agreement with the simulation results. The difference of response of angle of attack is less than 0.5°. The effect of stability augmentation and attitude control law was validated in the test, meanwhile the feasibility of virtual flight test technique treated as preliminary evaluation tool for advanced flight vehicle configuration research was also verified.

1. Introduction

The static test data supplemented by small-amplitude forced-oscillation tests for damping derivatives was used in the linear aerodynamic formulation in early time, and control system design was based on the linear control theory. The flying qualities and controllability were finally validated through flight dynamic simulation and flight test. This method and technological process have been proved to be very successful in moderate alpha sub-stall operation. However, specifications of modern combat aircraft require high manoeuvrability and agility at extremely high angles of attack. Unsteady aerodynamic effects such as flow separation and vortex bursting continue to be challenges for experimental aerodynamics, control system design and structural dynamics.[1] The coupling between them and the potential threats to flight safety need to be validated

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by flight test eventually. But flight test always comes last during the current serial development process. Wind tunnel based virtual flight test (WTBVFT) provides a way to evaluate and validate flight control system in wind tunnel.[2,3] It is intended that flight control system design can be conducted parallelly with aerodynamic development to not only shorten cycle times and reduce the technical risks of aircraft development, but also validate the physical control circuit.[4–7]

WTBVFT is a novel testing technology on which many researchers have done fruitful research work in recent years. Lowenberg have developed a dynamic model for the dynamic test rig in a 1.1 m wind tunnel with open test section, aiming to solve problems about mechanical friction and support strut-aircraft multi-moving-body mathematical modeling.[8–11] Gatto employs the similar 3-degree-of-freedom (DOF) and 5-DOF dynamic rig to identify stability derivatives and control derivatives in $9\ \text{ft} \times 7\ \text{ft}$ ($1\ \text{ft} = 0.3048\ \text{m}$) wind tunnel.[12–14] The three-axis steady and dynamic derivatives of M2370 flight vehicle and BAe Hawk model were obtained from the time histories under excitation signals. This method has the advantages of simple and flexible operation. The majority of small- and large-amplitude motion rigs are basically single DOF mechanisms, moving in pitch, yaw, roll or heave. These testing techniques and devices generally can only obtain a fraction of the required aerodynamic derivatives. This situation, unfortunately, has compelled the designer to use multiple techniques to obtain the critical design data required, resulting in the costly and labor intensive test programs that are common practice today.

Pattinson observed large-amplitude self-sustaining pitch oscillations of a model aircraft using a 5-DOF maneuverable rig. A phenomenological model incorporating dynamic stall was proposed to study the possible cause for these oscillations.[15] Araujo-Estrada et al. validated the capability of the new version of the maneuverable rig to physically simulate aircraft upset/departure behavior.[16] Sohi developed a technique which enables an experimental estimation of the aircraft's spin characteristics in a horizontal wind tunnel.[17] These application examples show the capability of virtual flight test (VFT) in wide range of various maneuvers. For the closed-loop control of nonlinear aerodynamic phenomenon, Davison modeled the limit cycle oscillation observed in an unforced pitch-axis single DOF rig,[18,19] and then a 'dynamic gain schedule' controller which schedules state feedback gains against themselves was adopted to improve transient response in nonlinear regions.[20] Khrabrov et al. proposed a 3-DOF dynamic rig mechanism, which has an above-fuselage support strut oriented along the wind tunnel flow.[21] With the 3-DOF dynamic rig, Grishin applied gain scheduled H_∞ control technique to construct a control law that suppresses the wing rock motion at high angle of attack.[22] In the aspect of control law validation and investigation, Yuji et al. studied self-repairing flight control system (SRFCS) in simulated failed actuator and damaged control surface conditions.[23] Flying quality researches were conducted with 3-DOF configuration; the robustness and re-configurability of flight control system were tested with 6-DOF configuration. Strub designed a pitch axis autopilot with H_∞ robust technique for a canard-guided projectile on a 3-DOF gimbaled structure.[24] The autopilot had good tracking of the reference signal while minimizing the effects of disturbances on the system output. Stenfelt studied the directional control issues of a tailless aircraft with a single DOF rig. Control laws designed by means of classical control theory were implemented for testing split flap in a wind tunnel at different airspeeds and angles of attack.[25] A typical missile was numerically simulated, and the verification VFT tests were performed in a 2.4 m transonic wind tunnel.[26,27] Guo et al. compared the dynamical characteristics of prototype aircraft with the scaled-model supported by a 3-DOF vertical strut in low speed wind tunnel.[28] Lee developed a magnetic suspension and balance system (MSBS) for measuring aerodynamic forces and moments and validating a height hold controller of a micro air vehicle (MAV). This kind of model support systems can eliminate aerodynamic interference and the friction of the bearings.[29,30]

Control augmentation system (CAS), the most basic and important part of flight control system, can improve the stability and handling of aircraft. It is widely used in civil airplane, transport aircraft and combat aircraft. If CAS can be validated in wind tunnel during the early design phase, the design and scheduling of control law will be pushed ahead. This paper details a 3-DOF gimbaled mechanism to connect a model with control augmentation system to a vertical support strut. The attitude sensor, embedded flight control computer and actuators were mounted in the model. The simulation and test results indicate that the attitude of the vehicle is stable and controllable. There is application prospect of the technique to investigate new aircraft configurations, flight control algorithm and advanced control method. With the benefits of cost, safety and efficiency, aerodynamic/flight/control integration evaluation can be implemented at early design stages.

2. Experimental setup and method

2.1. Support rig

The model is ventrally suspended at the center of wind tunnel (Fig. 1). The joint point is coincident with the center of gravity of the model. The model is connected to a bake lite rod via a rolling contact type ball gimbal with 3-DOF, which is connected rigidly with the model using an aluminum joint. The bake lite rod is connected to the aluminum frame located at the ground turntable through a flange at the bottom. Four steel cables are tightened to enhance the rigidness of the support rig at four corners on the top of aluminum frame. The gimbal with low mechanical clearance contributes small rolling friction force. The range of motion permitted is 45° in pitch and roll, and 360° in yaw. The gimbal is shown in Fig. 2.

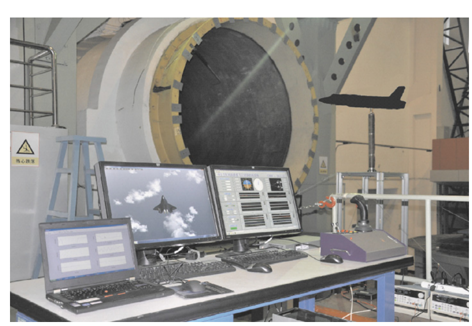

Fig. 1 Photo of virtual flight test in wind tunnel.

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