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FREE FLIGHT TEST IN HORIZONTAL WIND TUNNEL WITH POWERED AIRCRAFT

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Abstract

Modern advanced layout aircraft is faced with multi-disciplinary coupling problems such as aerodynamic layout and flight control system design. In order to carry out aerodynamic/flight/control integration research at the early stage of design, shorten the development cycle and reduce the development cost, a model free-flight test system was established in 8m×6m open wind tunnel based on similarity criterion. The system designs the scale verification machine model according to the mass inertia similarity criterion, uses the ducted fan to provide power for the model, invents the flight control system based on the embedded high real-time processor, and establishes the airborne measurement system with inertial sensor and wind vane, UWB (Ultra Wide Band) wireless carrier communication technology is used to realize model spatial position measurement. On this basis, the system is modeled and simulated, and the closed-loop stability increasing control law is designed to realize the stable flight at the trim angle of attack. The test results show that the horizontal wind tunnel model flight test can truly and accurately reflect the aerodynamic and control characteristics of the aircraft, and it provides a new technical support for the coupling discipline research of advanced layout aircraft design.

Keywords: Wind tunnel test, Free-flight test, Flight control system, Powered model, Similarity criterion

1. Introduction

NASA Langley Research Center has been working in large open low-speed wind tunnel (30ft) since 1950 × 60ft full scale low speed wind tunnel and 14ft × In the 22ft subsonic wind tunnel, 1ft = 340.8mm), the wind tunnel model free-flight test technology has been developed, which has been successively used for flight control verification of aircraft with variable swept wing layout, research on high angle of attack stability and control characteristics, development of thrust vector control technology, optimization of flight control law of aircraft with flying wing layout, etc[1-4].

Figure 1 – Free-flight test in wind tunnel of NASA Langley Research Center

China Aerodynamics Research and development center, China Aerospace Aerodynamics Research Institute and China Aerospace Aerodynamics Technology Research Institute have carried out research on the free flight test technology of wind tunnel model.
Modern advanced aircraft put forward higher requirements in aerodynamic layout and flight control design. Traditional design method optimizes the aerodynamic layout through the aerodynamic data obtained from the wind tunnel test in the early stage of aircraft development, and optimizes the flight control system through the flight data obtained from the flight test in the later stage of aircraft development[5-7]. Conventional static and dynamic tests can only provide the aerodynamic characteristics of the aircraft body, but can't provide the comprehensive characteristics after adding the closed-loop flight control system. The flight control system can be effectively verified through the atmospheric model flight test. However, under the condition of insufficient mastery of aerodynamic and flight control characteristics, this test method has high risk and high cost. Free flight test in horizontal wind tunnel with dynamic model makes up for the shortcomings of traditional design methods[8-9]. It is a transitional link from conventional wind tunnel test to atmospheric model flight test and it can effectively verify the overall design and flight control in the early stage of aircraft development. The test method of aerodynamic/flight/control integration is realized, and the development efficiency of aircraft is greatly improved[11-14].
Wind tunnel free flight test is to simulate the flight of real aircraft in the wind tunnel environment, and obtain high-quality test data by using the characteristics of stable wind tunnel flow field, so as to analyze the flight quality of aircraft, study the aerodynamic characteristics of aircraft, simulate the flight faults of aircraft, etc. The model design meets the similarity principle of size, mass and inertia to ensure the comparability between wind tunnel test data and real flight data; The electric ducted fan engine is used as the power; The flight control computer, attitude measurement, air flow angle and velocity pressure measuring sensor are installed inside the model; The model rudder surface is controlled by the driving mechanism of micro steering gear; Considering the movement range of the model and the safety of the test, the open test section of the 8m low-speed wind tunnel is selected. The security protection system is arranged above and below the model, and the real-time position measurement of the model is realized based on UWB wireless carrier communication technology. On this basis, the system is modeled and simulated, and the closed-loop stability increasing control law is designed to realize the stable flight at the trim angle of attack. The flight control system is shown in Figure 2.The wind tunnel free-flight test system is shown in Figure 3.

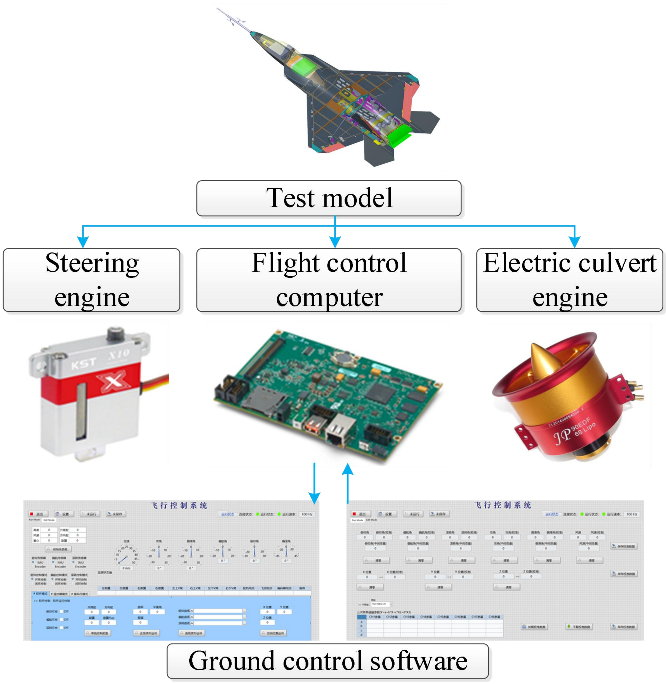


Figure 2 – Flight control system

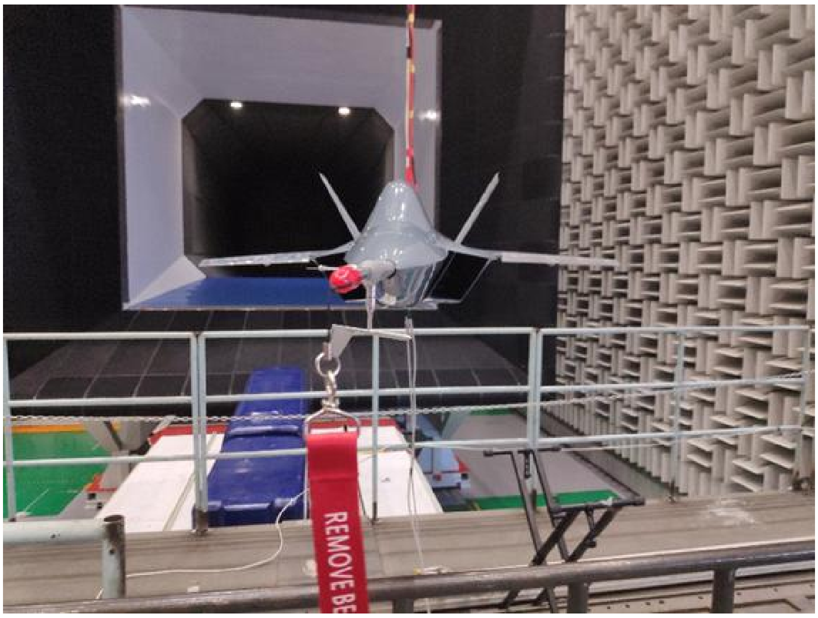


Figure 3 – Wind tunnel free-flight test system

2. Theory and simulation test

2.1 Similarity criterion

The wind tunnel free-flight test should meet the similarity criteria to truly reflect the full-scale prototype characteristics. Unlike the conventional wind tunnel test, free-flight test can only simulate some similar parameters. For the free-flight test of low-speed wind tunnel model, the influence of Ma number on aerodynamic force can be ignored in general. Therefore, the main similarity parameters are: Froude number Fr, Strouhal number Sr, Reynolds number Re, geometric similarity, mass similarity, inertia similarity and thrust similarity. In the test, the six degrees of freedom of motion of the model were fully released, which was consistent with the actual flight. For the stability and control characteristics research test that can not be ignored compared with the inertia force, Fr is the similarity criterion that must be met; During the test, 1g flight of the aircraft and small maneuvering flight near 1g trim state are mainly carried out, which does not involve unsteady processes such as rapid maneuvering, so Sr can not be simulated; In addition, it is impossible to simulate Re and Fr at the same time in the wind tunnel test. Under the above conditions that Fr must be simulated, it is impossible to simulate Re, which can only be considered in the test results. Note and analyze the effect of Re[15-17].

The scale model satisfies the similarity relations, including the geometric dimension, mass inertia , inertia similarity and the position of the center of mass. The flight control system satisfies the similarity relations, including the structure of the control law structure, the structure of the control law parameters and sampling frequency[18-19].

2.2 Control system design

The aerodynamic database is established through conventional wind tunnel test, so as to establish the kinematics and dynamics model of the aircraft, design the flight control algorithm, and verify the feasibility of the control law algorithm through digital simulation. The software and hardware of the embedded control system are designed according to the requirements of free-flight test, and the flight control algorithm is integrated into the embedded control system. The functions of the embedded control system, sensors and actuators are verified by hardware in the loop simulation. Finally, the free-flight test is carried out, and the structure and parameters of the control law are adjusted online to complete the design of the flight control system. The above process is iterated continuously until the flight control system meeting the test functional requirements. In July, 2020, the free-flight test was completed in the FI-10 wind tunnel of AVIC Aerodynamics Research Institute.

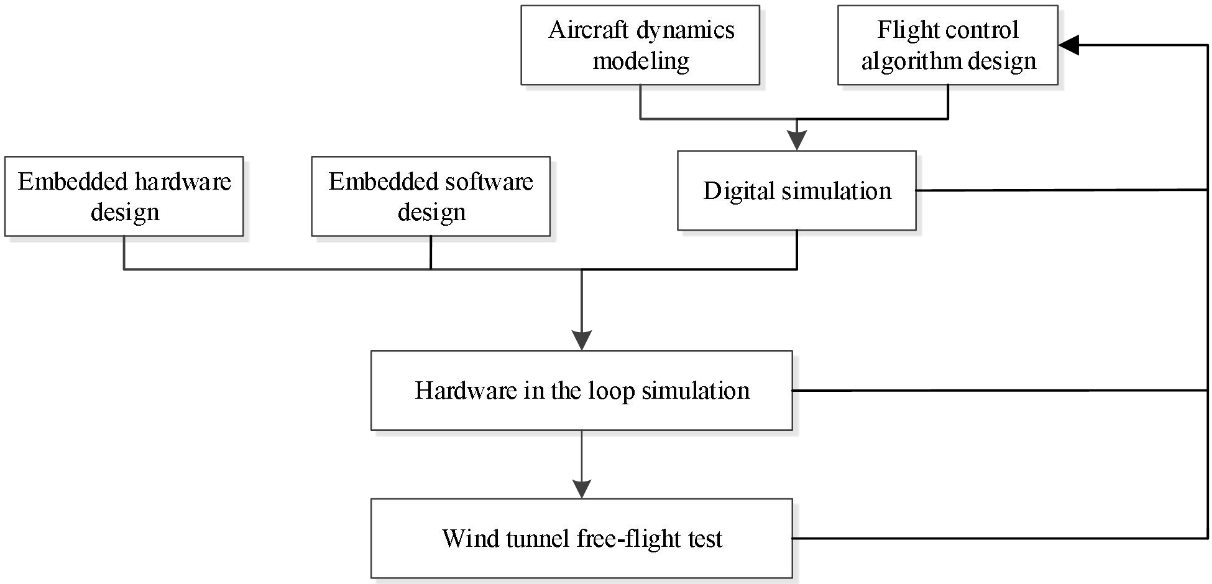


Figure 4 – Procedure for development of the free-flight control system

2.3 Digital simulation

The aerodynamic database and six degree of freedom state equation of the aircraft are established based on Matlab/Simulink, and the control law is designed. The digital simulation system is an ordinary PC, the simulation environment is Matlab/Simulink, and the visual simulation environment is Prepar3d. The simulator runs the kinematic and dynamic mathematical models of the aircraft, and the control law algorithm, sends the aircraft position, attitude and other information to the visual machine through network.

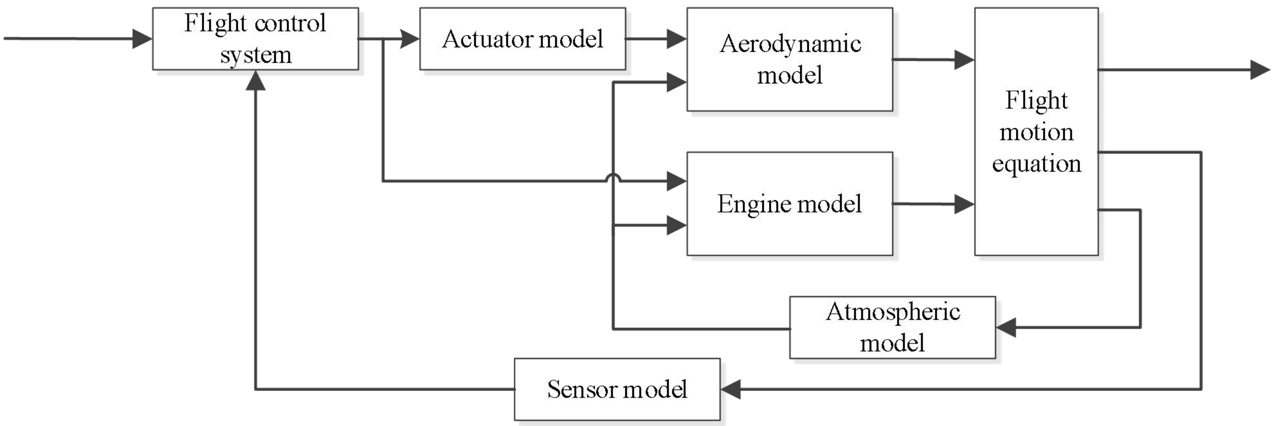


Figure 5 – Flight control simulation system

2.4 Flight control system design

The main control system is an ordinary PC, using Windows system and running LabVIEW software. It is mainly used for human-computer interface interaction, displaying test data and sending control instructions. The flight control system is a compactRIO embedded controller. The RT(Real Time) part runs NI Linux real-time operating system. This part is divided into high priority tasks and common priority tasks. The high priority tasks include data acquisition and processing of each sensor, running control law algorithms, command receiving and processing of the control mechanism, completing communication with the FPGA part, reading FPGA data, and sending FPGA instructions; The common priority system includes communication with the main control computer, sending the data of the main control computer and reading the instructions of the main control computer. The FPGA part realizes the configuration of signal port through reconfigurable FPGA, and completes the control of steering gear and culvert fan.

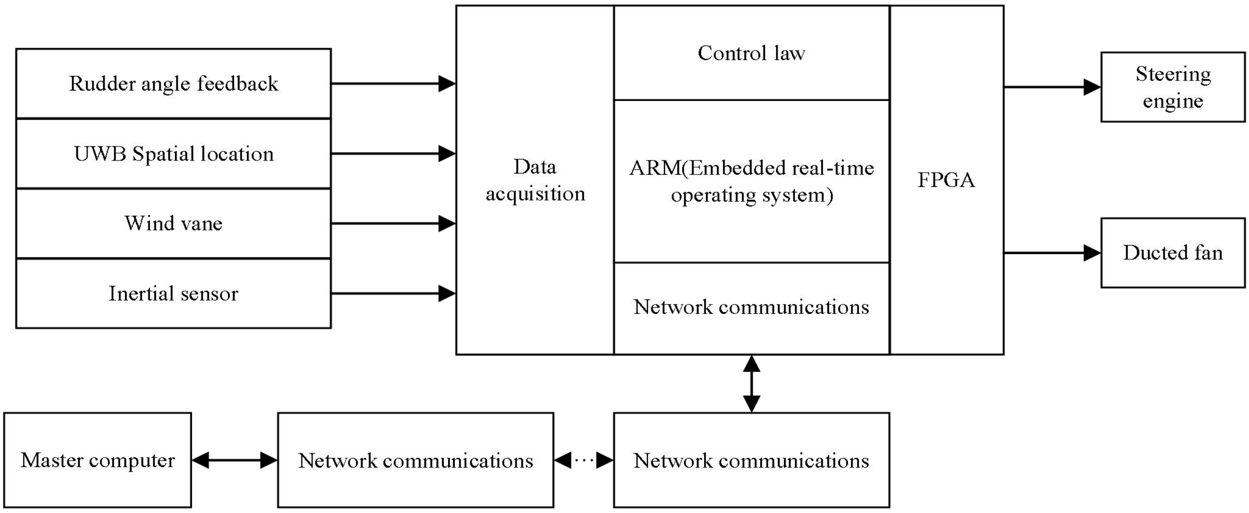


Figure 6 – Control system architecture

2.5 Hardware in the loop simulation

The real flight state of UAV is simulated in the hardware in the loop simulation system. According to the ground station control command and fault injection command, the flight control computer calculates and outputs the rudder deflection command in real time, then the rudder deflection command is sent to the real-time solution model to form a closed loop, so as to achieve the purpose of verifying the flight control system[20].

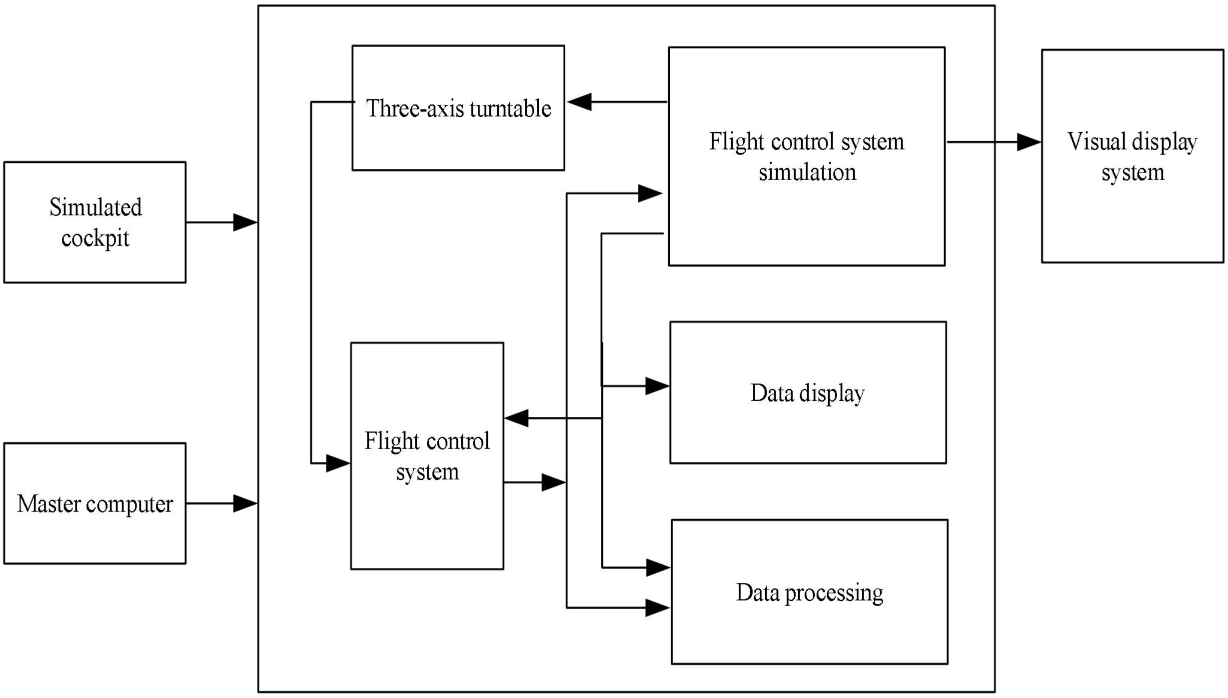


Figure 7 – Hardware in the loop simulation

Digital simulation digitizes all objects, and establishes the aircraft Matlab/Simulink simulation model system, such as aerodynamic model, mass characteristic model, mass characteristic model, motion equation model, control system model, etc.The Matlab/Simulink simulation model of the aircraft is transformed into the runnable code of the rapid prototype simulation platform, and the algorithm is downloaded and the parameters are modified in real time. The flight status of the aircraft is displayed through the visual simulation system and flight simulation VR equipment.Hardware in the loop simulation is to gradually materialize the hardware on the basis of digital simulation, and gradually verify the system functions of each physical object, such as the flight control computer and the inertial senor. The flight control computer and the inertial senor replace the mathematical model of the flight control computer and the inertial senor running in the rapid prototype simulation platform, The attitude position signal calculated by the flight simulation mathematical model running in the rapid prototype system simulation platform is output to the three-axis turntable (the inertial senor is fixedly connected with the three-axis turntable), the inertial senor signal is connected to the flight control computer, and the flight control computer outputs the calculated control surface signal to the rapid prototype simulation platform to verify the functions of the flight control computer and the inertial senor.The main control computer can synchronously record and display test data and curves according to test requirements.The test personnel can control the mathematical simulation model of the aircraft by simulating the flight control system, so as to realize the man in the loop control and make the test personnel truly feel the flight state of the aircraft.

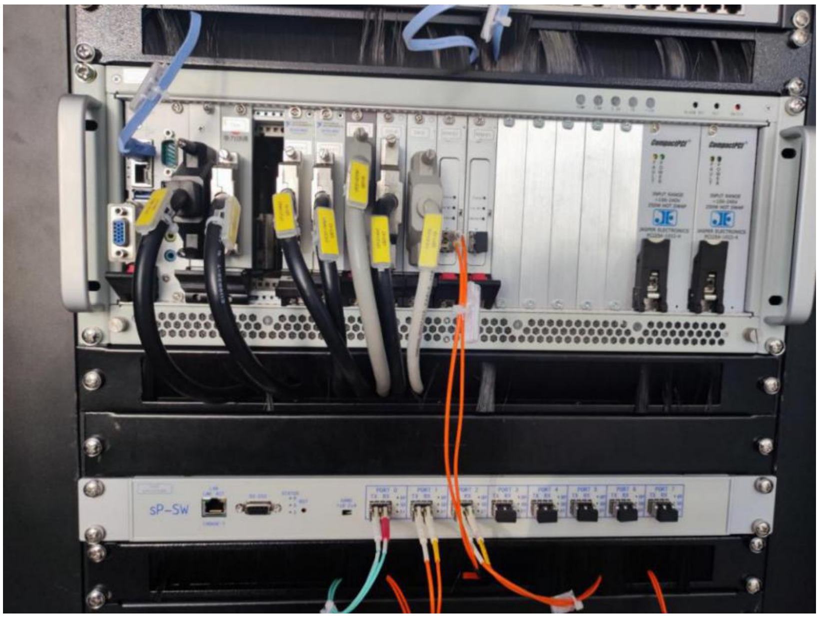


Figure 8 – Rapid prototyping simulation computer

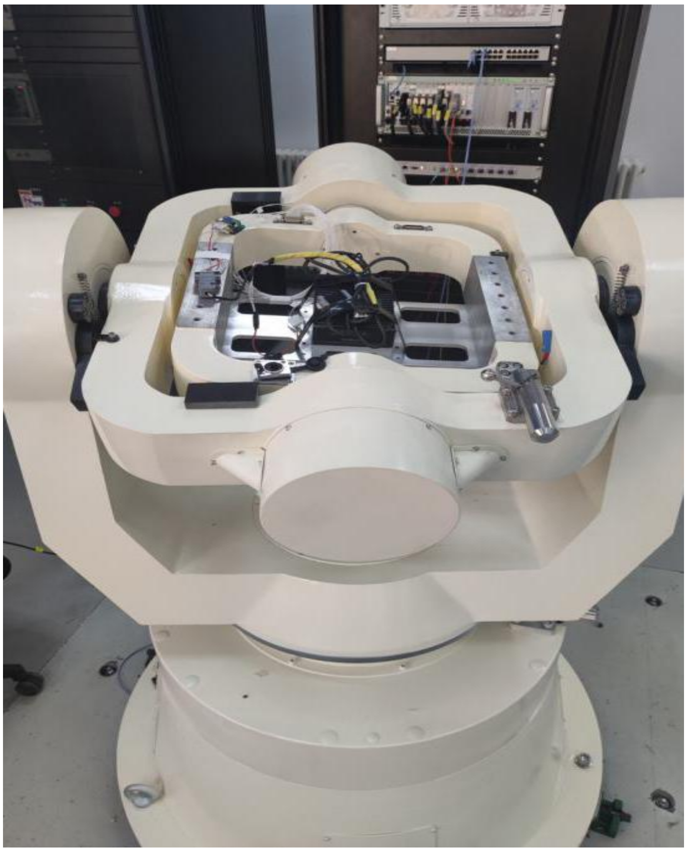


Figure 9 – High precision three-axis turntable

Figure 10 – Visual display system

3. Test analysis

3.1 Test Process

A test system has been established in the FL-10 wind tunnel of AVIC. The wind tunnel is a reflux low-speed wind tunnel with open/closed test sections. The designed maximum wind speed of the open test section is 85m/s, and the designed maximum wind speed of the closed test section is 110m/s. The test section is 8m wide and 6m high. The wind speed commonly used in the wind tunnel free flight test is 10m/s~40m/s, and the model size is 2m. The open test section is selected for this test.

The free flight test process of the wind tunnel is as follows:

① The model is hoisted in the wind tunnel through the safety rope, and the length of the upper and lower safety ropes is adjusted to make the aircraft model in the central area of the wind tunnel test section;

② Open the closed-loop control and wind;

③ Increase the wind speed to the test target wind speed. During this process, adjust the length of the safety rope and the throttle opening to make the aircraft gradually enter the trim flight state;

④ When the target wind speed is reached, the aircraft model can maintain 1g level flight in the central area of the wind tunnel flow field through the operation of the operator;

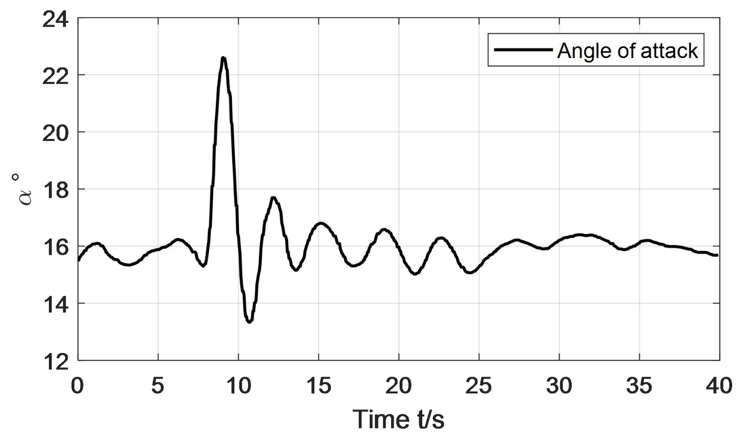
⑤ Carry out flight test verification of each subject;

⑥ Stop the wind, reduce the throttle opening and tighten the safety rope, and close the flight control law after the model stops stably;

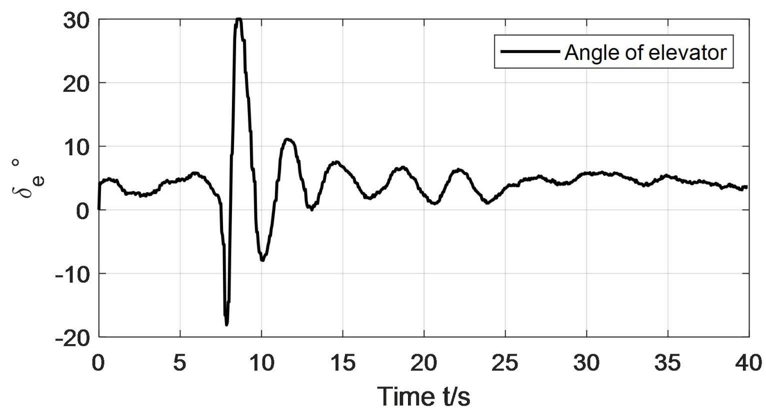
⑦ After the test, analyze the motion parameters during the test.

3.2 Test data analysis

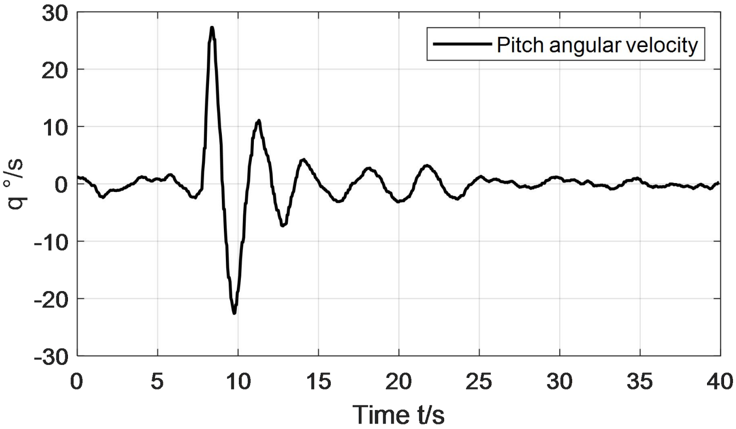
The scaled model flies at 16° angle of attack trim in the center range of the open test section of the wind tunnel. Given the angle of attack dipole wave command, the flight control computer collects the angle of attack, pitch angle velocity, angle of elevator and control command during the test, as shown in Figure 11.



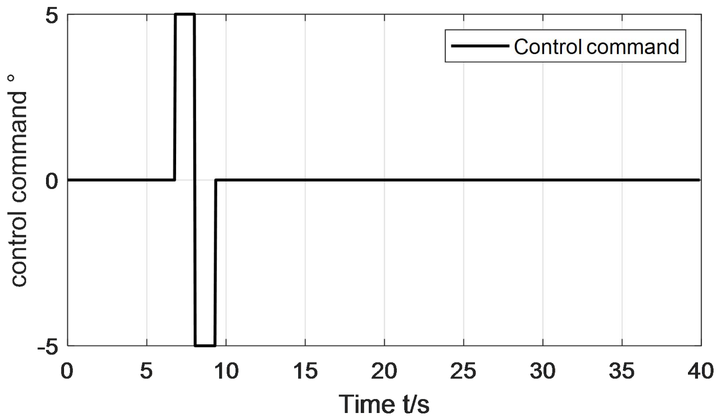
（a）Angle of attack



（b）Angle of elevator



（c）Pitch angular velocity



（d）Control command

Figure 11 – Wind tunnel flight test data

4. Conclusion

1) In order to make the response characteristics of the scaled model aircraft reflect the characteristics of the prototype aircraft, in addition to the dynamic similarity of the model, when constructing the flight control system of the model aircraft, the characteristic parameters and performance indexes of the flight control law, the system sampling frequency and the components of the system should meet the corresponding similarity proportion relationship.

2) The wind tunnel free flight test platform is built, and a series of methods such as control system design, digital simulation, hardware in the loop simulation and wind tunnel test are established, which is conducive to improving the dynamic test capability of the wind tunnel and engineering application.

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