WIND TUNNEL FREE-FLIGHT TEST FOR FLIGHT DYNAMICS AND CONTROL SYSTEM EXPERIMENTS

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Abstract

In recent years, there has been an increase emphasis on the potential transition of advanced flight control techniques or radical aircraft configurations to industrial application. Thus require extensive validation testing and bring urgent demand for development of the relative ease, safety, and low cost of investigating infrastructure to flight dynamics and control system testing. As part of these efforts, the wind tunnel free-flight test facility has been developed. It utilizes powered dynamically-scaled vehicles flown in the tunnel test section that enable the application of subscale flight test results to full scale vehicles. This paper describes the development and application of the test technique. Implementation of hardware and software subsystems, experimental approach, the associate modeling and flight simulation procedure prior to free-flight test will be discussed as well as the application of the test technique to research on the stability and control characteristics of a research fighter aircraft.

1 Introduction

Flight control system design and flying quality evaluation have been recognized as significant challenges for modern aircraft, especially for that of radical control techniques such as the capacities of vertical takeoff and landing, close formation flight, fault-tolerant and adaptive control, or unconventional configurations such as Blended-Wing-Body, Flying-Wing, Morphing aircraft and Tailless aircraft, etc. Without adequate understanding of the dynamics characteristics, or the complex phenomena for which computational prediction methods have not yet been developed or hard to model for flight simulation, full-scale flight test for flight dynamics and control system investigation would confront with excessive risk. So it is very important to develop ground-based facilities and corresponding experimental technique to enable designers to predict and analyse critical characteristics of new vehicles, including the stability, controllability, safety during flight or find the solution to modify unsatisfactory behaviour in the early design stages. In response to this need, it is currently developing a flight test method call wind tunnel free-flight test, using powered subscale flight vehicles flown unconstrained in a large-scale low speed wind tunnel, to effectively investigate and validate the necessary technologies not only with reduced or eliminative risk, but also have great advantages in reduce expenditure and time consuming.

This paper describes the development and application of the wind tunnel free-flight test infrastructure located at 8m×6m low speed wind tunnel of China Aerodynamics Research and Development Center (CARDC). The remainder of this paper is organized as follows: Section II describes the details of the Facilities, including implementation of subsystems and management of some key difficulties; Section III briefly discusses the associated flight simulator which is a very effective tool for pilots training and test procedure planning. Section IV provides insight into the wind tunnel free-flight test results, analyze the correlation with theoretical prediction and flight simulation results; Section V provides some concluding remarks.

2 Free-Flight Test Methodology

2.1 Architecture of the Facility

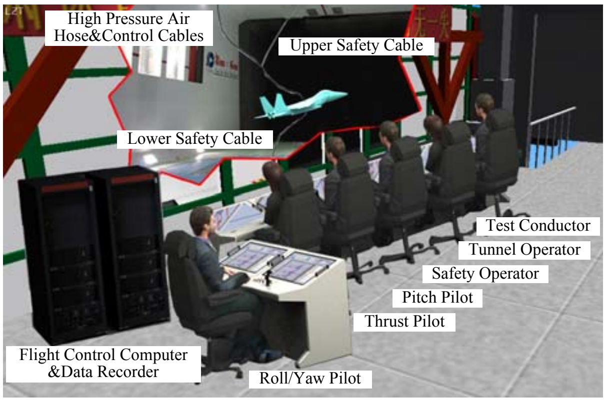

Fig. 1 Free-flight Test Facility in the 8m×6m Low Speed Wind Tunnel.

As shown in figure 1, the powered subscale model flown unconstrained in the airstream flowing through the tunnel test section, thus provides an experimental simulation environment which closely replicate the motions of the full-scale airplane. In order to properly represent the actual full-scale flight, the model must be dynamically scaled, includes scaling for dimensional, weight, inertia and control response. The demand of scaling for control response needs the model equipped with sensors to measure the motion parameters such as attitude, linear accelerations and angular rates, and with electro mechanical actuators onboard to move the control surfaces deflection. An external ground based flight control computer located in an adjacent control room besides to the test section of the wind tunnel is utilized to process the aircraft flight control law. Furthermore, to simulate the engines of full-scale aircraft, the model is equipped with ejectors supplied with compressed air exhausted from the rear of the model to generate demanded thrust. And to keep the model flown at a safety region, avoid hitting the wall of the tunnel test section, there are two safety cables linked the model to the top wall and the bottom wall of the test section. The piloting task is splitting between a pitch pilot, roll/yaw pilot and thrust pilot for the reasons described below in section *G*. And there is also a safety-cable operator to make the safety-cable kept slack during the test to minimize its effect on the model motions and restrain the model when the flight motion develop to uncontrolled or during the tunnel start-up or terminate the test. The pitch pilot, thrust pilot and safety-cable operator are sat at one side of the test section nearing the observation windows with a good view of the model longitudinal motions. The roll/yaw pilot observes the lateral motions by a view from behind the model provided by a video camera located downstream of the test section.

2.2 The Low Speed Wind Tunnel

The 8m×6m low speed wind tunnel locates at China Aerodynamics Research and Development Center, as shown in figure 2. It is an atmospheric, open-circuit tunnel with two fully closed test sections, the first test section(larger) is a rectangular parallelepiped with a dimension of 12m×16m×25m (width×height×length), with velocity ranges from 5 to 20m/s, and the second(smaller) test section is also a rectangular parallelepiped with a dimension of 8m×6m×15m (width×height×length), with velocity ranges from 15 to 85 m/s. The test section airflow is produced by three motor fans. The wind tunnel is ideally suited for low-speed tests to determine high-lift stability and control, aerodynamic performance, rotorcraft acoustics, turboprop performance, and basic wake and airflow surveys.

In consideration of the dimension and velocity range, the second test section is selected to be the ideal environment for developing of the free-flight test technique.

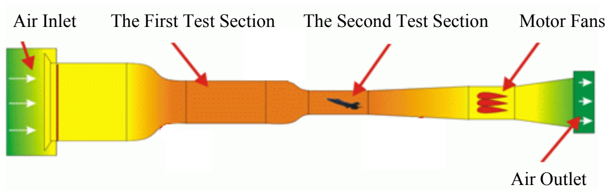

Fig. 2 The Sketch of the 8m×6m Low Speed Wind Tunnel

2.3 Dynamically Scaled Model

Relative to static testing model size, weight and inertia are significant important similarity parameters in the dynamic test techniques. Table 1 lists out the dynamic scaling relationships for free-flight test. The model scale should be determined by comprehensive consideration of the following factors: It should afford enough space to utilize onboard instrumentations in the airframe, and still have capacity of adjusting the weight and inertia to meet the similarity demand. The maximum size of a free-flight model is constrained by the size of the tunnel test section, normally with wing span of the model not be more than 1/5 the width of the section. Larger models will result in insufficient maneuvering space. All these factors lead to be very challenging for designing and manufacturing of free-flight models.

The platform used 10% scale of a general research fighter aircraft as the test model, with the characteristics of relaxed longitudinal static stability. To overcome the challenges of meeting the principles of similitude, the computer aided design software was used to allowing the designers to generate a 3-d solid model of the airframe equipped with all the onboard instruments. All of the vehicles components were modeled as accurately as possible to reflect the mass properties and structure characteristics. All required fasteners, adhesives, primer, and paint was included in the solid model to accurately estimate the vehicle weight and inertias. Thus made great contribution to the success of model design. After manufacturing and assembly of the vehicle, the weight and inertias were measured in the laboratory and found to be within 0.5 % for the weight and within 2% for the inertias of the estimated values.

Table 1 Dynamic Scaling Parameters for Free-Flight Test

Parameter	Scale Factor
Linear dimension	N
Relative density($m/\rho l^3$)	1
Froude number (V^2/lg)	1
Weight, mass	$N^3\sigma^{-1}$
Moment of inertia	$N^5\sigma^{-1}$
Linear velocity	$N^{1/2}$
Linear acceleration	1
Angular velocity	$N^{-1/2}$
Angular acceleration	N^{-1}
Time	$N^{1/2}$
Reynolds number (Vl/ν)	$N^{3/2}\nu/\nu_0$
Dynamic pressure	$N\sigma^{-1}$

2.4 Onboard Instrumentation

The aircraft is equipped with an attitude heading reference system(AHRS), which outputs filtered 3-axis linear acceleration measurements, angular rate measurements, estimated attitude angles. A micro-IMU which provides redundant and low latency 3-axis linear acceleration and angular rate measurements is also installed. A boom-mounted α/β vane sensor installed from the nose of the model is utilized for angle of attack and sideslip measurements, the data is corrected for angular rates, then made up-wash, side-wash corrections to the a data based on static wind tunnel calibration test results obtained previously. And the dynamic pressure measurement comes from a transducer installed in the wind tunnel, rather than air data probe onboard. The models are typically outfitted with electro mechanical actuators to move the control surfaces such as elevators, ailerons, and the rudder.

From scaling and similitude requirements, the resulting subscale model response is faster than a full scale model by a factor of $N^{1/2}$. Thus the dynamic performance of sensors and actuators should be better than that of the full-scale aircraft. Table 2 list the main specifications of the instruments used onboard which are selected from commercial-off-the-shelf products under considerations of volume, weight and performance.

Table 2 Specifications of Instruments Used Onboard

Instrument	measurement	specifications
Attitude Heading Reference System	acceleration, angular rate, attitude angle	±20 g, 0.1% of FS non-linearity; ±600°/sec, 0.5% of FS non-linearity; ±180°, Accuracy ±0.5° ; 30 Hz frequency response
Inertial Measurement Unit	acceleration, angular rate	±10g, 0.1% of FS non-linearity; ±600°/sec,0.1% FS non-linearity; 50 Hz frequency response
α/β vane	Angle of attack	range: -90° to +90°
	Angle of sideslip	range: -45° to +45°
Actuator	Drive surfaces	Continuous torque:100Ncm; No load speed: 400°/sec

2.5 Engine Thrust System

The engine thrust system provides model with adequate thrust to maintain at trim flight condition, simulates the function of engine for the full-scale aircraft. The basic requirements for the system including: provide the model with enough thrust, has fast dynamic response, and produce minimal effect on the motion of the model. According to different circumstances, there are two options of thrust system available, utilizing compressed air exhaust from ejectors to generate thrust or directly equip with small turbine engines.

In this platform, the model is equipped with a multiport ejector supplied with compressed air to generate thrust. The pressure of the compressed air keep constant during free-flight test and the thrust is modulated by adjusting the flow rate via a control valve. Before implementation of free-flight test, the ejectors were calibrated at wind-off conditions. Figure 3 shows the calibration result, with the pressure of compressed air maintain at 4Mpa. Further ground testing involved step changes in throttle position, and measurement of the responded thrust.

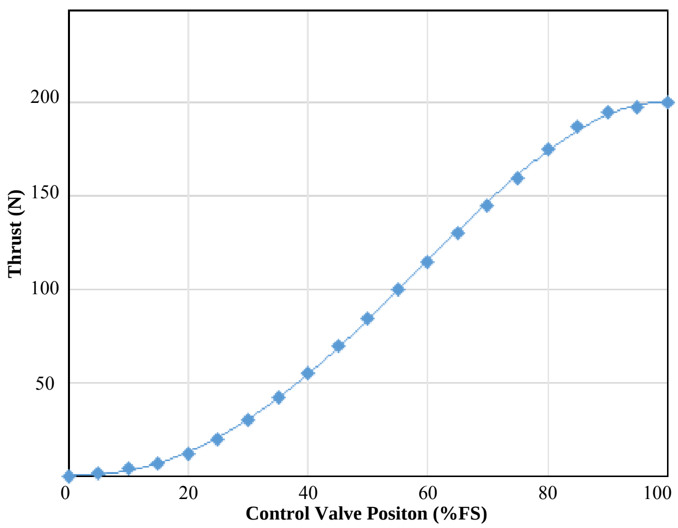

Fig. 3 The Static Thrust Calibration of the Engine Thrust System

In order to decrease the time delay in thrust response, the control valve is installed at the top wall of the tunnel test section to shorten the length of flexible compressed air hose from the valve to the ejectors in the model. And to minimize the effect of the hose constrain motion of model, a single degree-of-freedom rotational connector is installed near the center-of-gravity to enable the nose of model free to wander from side-to-side.

2.6 Flight Control System

Flight control system acted as the integrate subsystem for the test platform, and is designed to be capable of accomplishing the following primary tasks:

1) Receive and process state data (e.g. sensor outputs, pilot control signals, etc.) in real-time, and transmit control surfaces and thrust commands to drive aircraft control surfaces or thrust control valve.

2) Process the researcher-provided flight control laws at real-time.

3) Permit researcher to adjust parameters online to change flight control laws or the test condition.

In consideration of the real-time computing requirements, the limited space and weight budget of the model, the flight control system is not onboard the model, but with external ground based computers located in an adjacent control room. It was independently developed by researchers with the hardware design to be powerful, multi-processor, distributed real-time simulation facilities with commercial-off-the-shelf computer equipment such as PCs and I/O boards. The communication interface including fiber reflective memory network, Ethernet, Serial ports, analog and digital IO signal acquisition system.

With the model-base design technique, the programming environment of the real-time software was designed to be seamless connection with the normal flight control law design environment which is based on tools developed by The Mathworks. It could automatically generate and download the execution code at each stage of development, avoid developing of the lower-level details of real-time code. Thus greatly reduces the amount of time to program and integrate the systems, achieve rapidly testing from digital simulation to free-flight test.

Due to the success in development of hardware and software for the flight control system, researchers can evaluate a wide variety of test conditions more rapidly than can be accomplished in the actual aircraft. Having the ability to quickly change conditions, or quickly reset to a specific initial condition, maximizes the amount of testing that can be accomplished in a given period of time. The model-based and open architecture feature also enable the platform to suitable for testing different kind of aircraft.

2.7 Operation Stations

The human-machine interface plays a critical role in enabling precise aircraft control and safety. As mentioned above, the model scale is reduced, the model dynamics responses are faster than the actual full scale aircraft. And he model flown in the tunnel test section with confined test area, thus increase the workload for the pilot to control. Furthermore, since the pilots are remotely located lacking of the feeling of acceleration which can result in some lag in the pilot response. All of these factors result in a high workload piloting task. Although it is possible for a single pilot to fly a model by operating all degree of motions, such an arrangement is not suitable for research purposes because the pilot must concentrate so intently on the task of keeping the model flying satisfactorily that he is not able to learn much about its stability and control characteristics. The piloting task is split to three pilots with operation stations respectively.

The operation station provides the inputs for flight control system to fly the aircraft manually or automatically. It provides all necessary pilot controls and a variety of displays for the pilots or researchers. The stations including a pitch pilot's control station, roll/yaw pilot's control station and thrust pilot's control station. The pitch pilot's control station equipped with a display screen to show the control command and the attitude of the aircraft in the form of curve or virtual aircraft instrument. And it also install with a joystick, the necessary knobs such as pitch trim knob and some switches, etc. The roll/yaw pilot's control station and the thrust pilot's control station have similar arrangement except some differences in pilot controls. Figure 4 shows a photograph of the roll/yaw pilot's control station.

Fig. 4 Photograph of the Roll/Yaw Pilot's Control Station

2.8 Other Subsystems

The platform also includes a voice communication subsystem to allow all participants in free-flight test activities to maintain voice contact. And all the communication information would be recorded.

A video monitor subsystem provides the capability to monitor the model in flight, especially, the video output signals from the camera located at downstream of the test section with a view of behind the model is transmitted to the roll/yaw pilots' station for pilot control. And other video signals from different view point are recorded as important test data for post analysis.

The data recorder sever recorded all flight data parameters from onboard sensors, the control signals from pilots and physical camera video outputs for post-flight analysis. And this system is configured to have capacity of playback of all recorded flight data parameters and camera video.

2.9 Experimental Approach

The wind tunnel free-flight test platform could support for integrative research on aerodynamics/dynamics/control characteristics of new-concept configuration flight vehicles, study of dynamic stability and control characteristics of aircraft flight at high angle of attack or with hardware failures or system faults(e.g. sensors or actuators failure, airframe damage, etc.), validation testing of advanced flight control algorithms or technologies prior to consideration by the aviation industry for transition to commercialization and certification. Furthermore, it could also be utilized for aerodynamics parameter estimation and dynamic modeling identification, to generate accurate mathematic model for flight simulation or experiment reproduction.

Due to the model based design of the hardware and software architecture, the free-flight test facility could be used to test various researcher-provided control laws and aircraft configurations. For a new aircraft that to be tested, the first thing to do is determine the scale factor by comprehensive consideration of achieve sufficient maneuvering space, have enough inner space to install onboard instruments, be able to adjust to meet the mass and inertia requirements, and the effect of scaling in Reynolds number to the problem investigated. These factors are usually contradictory which have to make a trade-off. After determine the scale factor and simulated altitude, the model can be designed and manufactured refer to the principle of similitude listed in table 1. And for this closed-loop control experiments, similitude scaling also requires that flight control computer speed and actuator rates are time scaled based on the full scale vehicle control system. If there are some factors that cannot meet the similarity criteria requirement, the effect should be carefully evaluated in interpretation of the test results.

The free-flight technique also has its limitations. Besides the Reynolds number scaling mentioned above, the technique is also limited to 1g maneuvers due to the generally slow speed response of the tunnel. Both of these limitations must be considered when designing flight experiments or applying results to full scale vehicles.

3 Modeling and Flight Simulation

It is apparent that a high degree of coordination is required in performing tests with this technique. And several challenges must be solved before implementation of free-flight test. For example, design of the experiment, pilots training, study of test results assessment method, etc. Therefore, here uses virtual reality tools and computer simulation technology to develop an immersive pilot-in-loop real-time flight simulation platform, which is extraordinary realistic simulation of the wind tunnel free-flight test environment, as shown in Figure 5.

In the simulation model, the non-linear six degrees-of-freedom flight dynamics model was developed by using data from previous wind tunnel tests along with the mass properties data. The dynamics response characteristics of sensors, actuators onboard and even the effect of the safety cables were also modeled. The model of wind tunnel had been developed too, simulated the tunnel start-up or stop progress and the transition progress at different airspeed. With the help of the simulation, the system integration testing, pilot training and experiment design were successfully overcome. Thus greatly promotes the process in application of the free-flight test technique, makes a significant contribution to the success of the free-flight test in the tunnel. The simulation also help for iterative optimization of the flight control laws along with tunnel test, or post analysis and interpretation of the tunnel test results via its function of experiment reproduction.

The flight simulator can also run in another mode as shown in Figure 6. The mode provides a real-time environment for researchers to make preliminary assessment at the early stage of flight control law design.

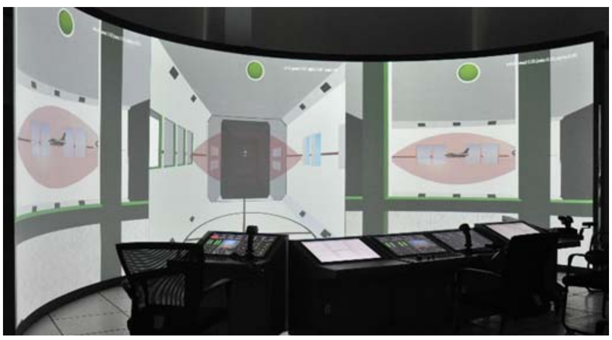

Fig. 5 Photograph of the Flight Simulator (Flight in the Wind Tunnel)

Fig.6 Photograph of the Flight Simulator (Flight in the Atmosphere).

4 Free-Flight Test

The above paragraphs descript the test methodology of using powered dynamically subscale aircraft model flown in the wind tunnel for flight dynamics and control system experiments, mainly based on the free-flight test facility and the associated flight simulator. To confirm that the test platform fulfills its intended purpose, a verification test was executed, to research on all phases of the experimental implementation, including flight control design and simulation, system integration and testing, flight test maneuvers planning, Pre-Deployment Training and operation rehearsals, and finally the free-flight test in the wind tunnel.

The verification test utilized the General Research Fighter Aircraft Model development by CARDC, which is 10% sub scaled, with instability in longitudinal dynamics. A command augmentation flight control law was designed and the flying qualities of the corresponding full-scale aircraft had been comprehensively evaluated by professional aircraft test pilot. Thus provides important reference for correlation study of free-flight test results and full-scale flight test results.

During the free-flight test, test conditions covered a variety of speeds and angles-of-attack, from zero to maximum coefficient of lift before stall and departure occurred. And qualitative and quantitative evaluation of the flight dynamics and control characteristics are illustrated as follows.

4.1 Qualitative Evaluation

The qualitative evaluation plays an important part in the test results, and it assesses the effectiveness of the flight control system by the results including time-history parameter recordings, pilots' comments, and pilots' rating base on Cooper- Harper Rating (CHR), as shown in figure 7.

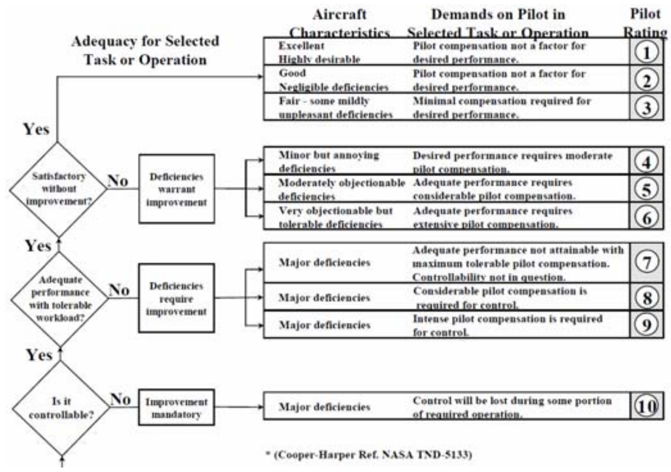

Fig. 7 Diagram of the Cooper-Harper Rating criteria

For each test condition with the model flight at steady 1g trim at a certain angle of attack, the free-flight test will be usually conducted repeatedly 3-5 times, with each running lasted for about 10 minutes. The first running is just for the pilots to adapt themselves to the operation of the model without giving any comment or rating for the test result. However, immediately after each following running, the test conductor will ask the pitch pilot and roll/yaw pilot to provide remark about controllability, workload to maintain lg flight, and level of pilot compensation respectively. Furthermore, they should also assign the rating while referencing the Cooper-Harper Rating scale flow chart. Note that for free-flight test, the pilot ratings are just used as relative indicators of handling qualities and it does not necessarily to be exactly equate with that of the actual full-scale aircraft. However, it could still be used to roughly predict the performance of the flight control laws with proper consideration of the ratings' corresponding relationship between free-flight test and full-scale flight test.

Table 3 presented an example of the pilot rating results obtained in this verification test. The results showed that the pilot ratings of the model are 3-6 during this flight envelope, while that of the full-scale aircraft are 1-3. The reasons that caused deterioration of pilot ratings could be explained as follows. First, the flight dynamic response of the model airplane is faster than the full scale airplane, thus increase the pilots' workload. Second, the model must be control to fly in the safety region of the tunnel test section, while the aircraft fly in the sky does not has the constraint. Finally, as mentioned before, the pilot in this study is piloting remotely just rely on sense of sight, lacking of the feeling of acceleration. These practical experience and correlation study provide reference for analyzing test results of the future free-flight test, assist pilots to make conclusion on whether the stability and controllability are adequate.

Table 3 An Example of Comments and Cooper-Harper Ratings From Free-Flights Test

1g Flight Condition	Performance	Pilot Compensation	CHR
$\alpha=5°$	Desired	Minimal	3
$\alpha=8°$	Desired	Minimal	3
$\alpha=12°$	Desired	Moderate	4
$\alpha=15°$	Desired	Moderate	4
$\alpha=18°$	Adequate	Considerable	5
$\alpha=21°$	Adequate	Considerable	5
$\alpha=25°$	Adequate	Extensive	6

With the qualitative evaluation, flight control system gains can also be adjusted to arrive at acceptable flying qualities, or find solutions to avoid the undesired dynamics. For the behavior of a configuration proves to be unsatisfactory, methods for achieving satisfactory characteristics can be studied by configuration changes to the model, or by the adjustment of flight control laws. One of the greatest advantages of the free-flight test is, of course, the relative ease, safety, and low cost of investigating gross changes in aircraft characteristics.

4.2 Quantitative Evaluation

After achieve appropriate flight control system gains by qualitative evaluation, further study could be executed to get some quantitative results represent the stability and controllability characteristics. To support this test objectives, the test approach will involve measurements of the flight vehicle's motion parameters for a variety of maneuvers and flight conditions. Test maneuvers must be properly designed not only to obtain valid data for quantifying stability and controllability parameters by state-of-the-art system identification methods, but also limited by not to cause the aircraft to flight to the boundary of the safety region which would tighten the safety cables. Different with the qualitative evaluation which the pilot's control objective is to maintain steady 1g trim flight, the control inputs will be superposed with steps, doublets, or frequency sweep signal.

Table 4 Model Dynamic Characteristics

Parameter	Model scale	Full scale	Level 1 requirement
Frequency of short-period mode	2.2Hz	0.7Hz	--
Damping ratio of short-period mode	0.83	0.83	0.35～1.30
roll mode time constant	0.22 sec	0.69 sec	<1.0 sec

Table 4 illustrates the model dynamic response characteristics for a certain flight condition which was obtained by performing doublet control inputs and identifying the resultant model motions. The dynamic response characteristics of the model were converted to full-scale values and compared with airplane handling qualities criteria Model. And the results showed good agreement with the prediction results from flight simulation at the normal flight envelop which the mathematical aerodynamic model had been developed accurately. The test results were well representative of actual full-scale airplanes. Thus for the condition for which computational prediction methods have not yet been developed or hard to model for flight simulation, The test technique may provide powerful tools for exploration.

5 Conclusions and Future Work

The wind tunnel free-flight test infrastructure has been successfully developed for flight dynamics and control system experiments. The test utilizes powered dynamically subscale models, representative of the full-scale aircraft, which can be tested in abnormal flight conditions or used to verify the radical design of flight control algorithms and configurations that are otherwise too risky for full scale testing.

Modeling and flight simulation is an integral and necessary part of the free-flight test, it is mainly used for vehicle development, flight test planning and pilots training, and control system research. To date, a high-fidelity universal simulator suitable for various aircrafts have been developed, and flight simulation of the model of the current flight has been executed for comparison with free-flight test.
Flight experiments are in progress that include qualitative and quantitative evaluation. The current flights are being made with a 10% sub scaled model, which serves as a general research vehicle for the advanced fighter aircraft. A verification test was executed, to research on all phases of the experimental implementation, including flight control design and simulation, system integration and testing, flight test maneuvers planning, Pre-Deployment Training and operation rehearsals, and finally the free-flight test in the wind tunnel. The free-flight test results show reasonable agreement with flight simulation and full-scale flight test in both qualitative and quantitative assessment, and this practical application experience has shown it to be a useful tool in exploratory investigations on flight dynamics and control system, especially for new types of aircraft or advanced flight control methods where there was no background of experience or hard to model for flight simulation. Future flight testing is planned for further study of the aircraft with some hardware failures or system faults, such as sensors or actuators failure, airframe damage, etc.

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