Presentation of Next Generation Transport Aircraft meeting

Development of hybrid flight simulator with multi-degree-of-freedom robot

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Abstract

The title of my talk is "Development of hybrid flight simulator with multi-degree-of-freedom robot". This presentation presents hybrid motion of an aircraft in wind tunnel to demonstrate and study dynamic flight phenomena such as a Wing rock and Dutch roll.

Recently, the fields in which aircraft are used are expanding dramatically. Higher performance is demanded of aircraft to achieve difficult tasks in diverse fields. For example, unmanned aerial vehicles (UAVs) have capabilities of acrobatic flight such as hovering flight and turnaround flight using post-stall maneuvers.

In such dynamic flight, dynamic effects during flight apparently influence flight conditions. Therefore, it is necessary to elucidate nonlinear flight dynamics including the effects of unsteady aerodynamics. Some conventional experimental approaches to these problems present numerous problems in reproducing identical conditions and aircraft behavior. To resolve these problems, we propose the use of hybrid motion (hardware-in-the-loop) simulation. Hybrid motion simulation is a promising method combining experimental fluid dynamics and numerical simulation of flight dynamics. It is useful to demonstrate arbitrary flight in a wind tunnel.

First, the concept and an algorithm of hybrid motion simulation are presented along with details of the system configuration of the simulator. A motion demonstration method is then described. Secondly, one-degree-of-freedom rolling motion of an aircraft model and its hybrid motion simulation are introduced. Finally, the plan of a multi-degree-of-freedom Hybrid Flight Simulator is explained.

Introduction

Recently, the fields of use of aircraft are expanding dramatically. Accordingly, higher performance is demanded of aircraft to achieve difficult tasks in diverse fields. For example, unmanned aerial vehicles (UAVs) can perform acrobatic flight that includes maneuvers such as hovering flight and turn around flight with post stall maneuvers. Concurrently, aerodynamic phenomena have attracted attention. Their characteristics must be comprehended more precisely for expansion of aircraft flight capabilities. In such dynamic flight, dynamic effects during flight apparently influence flight conditions. Therefore, it is necessary to develop nonlinear flight dynamics including the effects of unsteady aerodynamics. Some conventional experimental approaches to these problems are dynamic wind tunnel testing and free flight testing. Dynamic wind tunnel testing is useful to study the nonlinear aerodynamic behavior of an aircraft by oscillating or moving the test model in the test section. Thereby, the effects of frequency, amplitude, and unsteady flow on stability coefficient can be evaluated. Another approach is to calculate the flight dynamics to evaluate the aircraft stability numerically. Dynamic wind tunnel testing helps to elucidate basic dynamic effects on an aircraft model. Numerical calculation helps to ascertain the behavior of real-scale aircraft. Nevertheless, these methods show difficulty in producing the same conditions repeatedly and difficulty in adjusting stability parameters. To solve these problems, we propose the use of hybrid motion (hardware-in-the-loop) simulation, which combines experimental fluid dynamics and numerical simulation of flight dynamics. It can demonstrate arbitrary flight in a wind tunnel.

Past studies of hybrid motion simulation have been applied to simulate contact phenomena of on-orbit robot service. In this simulation, the modeling to contact is replaced by physical contacts of a robot.

At the same time, modeling to contact is calculated numerically. The force is measured in real time. This approach can help to simulate various phenomena for which the models for some physical processes are unknown or cannot be well described mathematically. It has not been used only to reproduce the contact phenomena. We propose the application of this concept to aerodynamic phenomena.

The objective of this research is to develop a new wind tunnel test technology to create arbitrary flight conditions in a wind tunnel using a hybrid flight simulator. We also develop a multi-degree-of-freedom robot to apply the multi-degree-of-freedom hybrid flight simulator.

Experimental method

The concept and the detailed system of hybrid motion simulation are explained next. The hybrid motion simulation system combines numerical simulation and experimental simulation. First, the F/T sensor measures aerodynamic forces and torques. The obtained data are input to the numerical models to calculate flight dynamics. The calculation result represents the aircraft model behavior under current wind conditions. Then that result is demonstrated by the robot. Thereby, the hybrid motion simulation is a closed-loop system.

The target of one-degree-of-freedom motion is the Wing rock motion of a delta wing model. The Wing rock motion is a self-induced limit cycle oscillation occurring at high angles of attack, and damping motion during a low angle of attack. The delta wing model is scaled as an aircraft model in this study. This phenomenon is discussed briefly from the aspect of aerodynamics. We produced a free rolling device to reproduce Wing rock motion. It includes an encoder to measure the Wing rock motion frequency.

To compare the Wing rock motion produced by hybrid motion simulation to that produced by a free rolling device, we also built a rolling motion device. The physical model and numerical model parameters must be adjusted to reproduce the aerodynamic phenomena. The rolling motion device contains a motor, a reducer, a torque sensor, and a motor deliver. The rolling motion device aims at imitation of the Wing rock motion. Furthermore, it can reproduce the large amplitude motion caused by aerodynamic forces. This device has one-degree-of-freedom flexibility and a feature whereby it can reproduce high-frequency motion.

This experiment was conducted in the Low-turbulence Wind Tunnel at the Institute of Fluid Science, Tohoku University. In this experiment, an open-type test section was used with an octagonal cross section. The test section width was 810 mm. The test section length was 1420 mm. The free-stream velocity was set at 50 m/s. The turbulence level of free-stream velocity was less than 0.4%.

Results and discussion

We first explain the results of free roll motion. Wing rock motion occurred at an angle of attack of 33 deg to 44 deg, under the wind of velocity = 10 m/s during wind tunnel testing using a free rolling device. The result of its frequency is 3.2 Hz at AoA =35 deg. Next, the result of hybrid motion simulation using a rolling motion device to reproduce wing rock motion is 1.15 Hz at AoA=35 deg, under wind of velocity=10 m/s. That result differs from the frequency measured using the free rolling device. Based on this result, we must find a method to increase the simulation accuracy.

The cause of the problem is mainly the delay in the way that the concept is implemented. In practical implementations, all components within the simulation loop—the motor, the sensor, the numerical calculation—are not functioning ideally. Therefore, we must consider their response delay. The main factors causing the delay of this system are attributable to the sensor. To cope with the problems described above and to demonstrate more realistic aerodynamic phenomena, the system configuration is improved.

To resolve this problem and to compensate for the sensor delay, we introduced phase-lead compensation (PLC). To estimate the delay time of the F/T sensor, we compared the frequency calculated from force data with that calculated from angular acceleration. We identified the delay time using this method. The result of PLC hybrid motion simulation is 1.95 Hz, which is much improved from the previous value. Because of the accuracy of identification of the delay time, the frequency of hybrid motion simulation is insufficient. However, the validity of this method can be inferred from this result. We plan also to apply this method for other delays.

Based on results obtained for this one-degree-of-freedom hybrid motion simulation, we propose multi-degree-of-freedom hybrid motion simulation. Different from the case of one degree of freedom, it is difficult to find sufficient data to verify the result of hybrid motion simulation. Therefore, we plan to do R/C flight tests to gather necessary data. We plan to obtain necessary flight data such as wind of velocity, model position and attitude, and thrust. If the hybrid motion simulator can reproduce the same phenomena as those measured using R/C flight test in the wind tunnel, then the effectiveness of the method can be verified.

A six-degree-of-freedom robot manipulator, HEXA-X2, was developed at Tohoku University as a parallel link robot manipulator with six degrees of freedom. The HEXA type parallel robot has high-frequency motion compared to a conventional serial robot system. It is designed to satisfy requirements for virtual flight in the wind tunnel in terms of workspace, moving frequency and degrees of freedom of motion. The HEXA-X2 characteristics include high rigidity and capability for high-frequency motion. To evaluate the HEXA-X2 performance, forced oscillation wind tunnel tests were conducted. The HEXA-X2 can demonstrate a Dutch roll motion at 3 Hz. However, HEXA-X2 has the inherent fault that its workspace is narrower than those of other robot manipulators. Therefore, we must consider these characteristics.

Conclusions and Future works

We developed a Hybrid Motion Simulator for dynamic wind-tunnel testing. A one-degree-of-freedom hybrid motion simulation was conducted to verify its capability to reproduce real flight conditions in the wind tunnel. For the multi-degree-of-freedom hybrid flight simulator, we developed a six-degree-of-freedom robot manipulator, HEXA-X2, to implement a multi-degree-of-freedom simulator with it. As future work, we plan to make an R/C model and use it to obtain flight data from flight testing. Subsequently, we will conduct wind-tunnel testing using those flight data, and validate the capability of the hybrid flight simulator. We also plan to visualize unsteady flow around the model to ascertain its effect on aircraft dynamics using methods such as the mini tuft method, pressure sensitive paint method, and the laser light sheet method. The mini tuft method can enable visualization of the flow directions and the position of vortex breakdown around a moving aircraft. This method is an extremely effective means to establish a multi-degree-of-freedom hybrid flight simulator.