Status of MSBS Study at KAIST

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ABSTRACT: This paper describes the status of Magnetic Suspension and Balance System (MSBS) study at KAIST. Dynamic calibration was performed for several experimental models in order to measure external forces and moments acting on the models. Aerodynamic forces and moments acting on the models were measured using an MSBS during wind tunnel tests while support interferences are eliminated. Subsystems for a new designed MSBS were tested.

1 INTRODUCTION

Aerodynamic forces and moments acing on an experimental model are generally measured through wind tunnel tests and the air flow around the model also can be observed by employing visualization schemes, such as Particle Image Velocimetry (PIV). During wind tunnel tests, the experimental model should be located at the center of the test section and mechanical supports are normally employed to fix the model and measure the aerodynamic forces and moments. However, the accuracy of the wind tunnel tests is easily decreased because these mechanical supports generate disturbances on the air flow around the experimental model. Magnetic Suspension and Balance System (MSBS) can be an ideal solution for support interference problems.

MSBS uses magnetic forces and moments to levitate an experimental model which is magnetized or has permanent magnets inside as shown in Figure 1. At the same time, MSBS can measure external forces and moments acting on the model so that mechanical supports are not required and support interferences are eliminated during wind tunnel tests [1].

In 1937, Holmes proposed that magnetic forces can be employed to reduce frictional forces of bearings [4]. Tournier et al. suggested that magnetic levitation devices can be employed during wind tunnel test in 1957 [11]. Since Vlajinac and Covert developed the world's first practical MSBS for wind tunnel tests [12], many researchers have employed an MSBS to eliminate support interferences during wind tunnel tests.

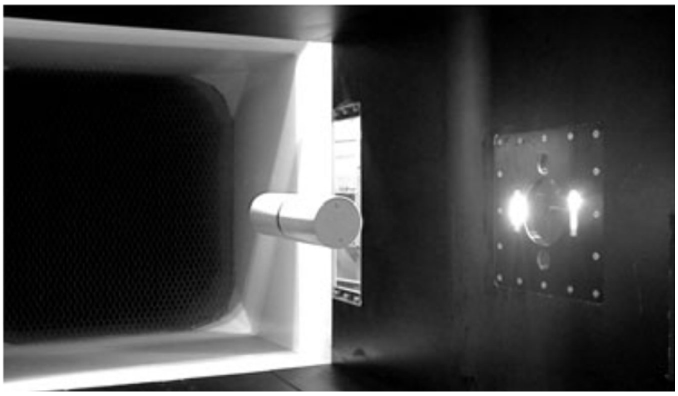

Figure 1. A cylinder model magnetically levitated in the 60 cm magnetic suspension and balance system in JAXA [3].

Owen et al. [9] measured aerodynamic coefficients of a cone with supersonic wind tunnel so that shock interference caused by mechanical support can be eliminated. Sawada et al. [10] employed an MSBS which is installed on a subsonic wind tunnel and measured drag coefficients of a sphere model without any mechanical support. Higuchi et al. [2, 3] performed PIV experiment during wind tunnel test with an MSBS in order to observe air flow around cylinder models and they measured drag coefficients of the models.

This paper discusses the status of MSBS study at KAIST. MSBS study at KAIST has been carried out with an MSBS developed by Y. Kawamura at FIT. A dynamic calibration method was employed for convenient multi-axis calibration of the MSBS, which makes good use of the advantages of MSBSs as not only non-contact type balance but also non-contact type actuator. Multi-axis aerodynamic forces acting on an experimental body during wind tunnel tests were measured with various aerodynamic models, such as a cylinder, a finite wing, and a Micro Air Vehicle (MAV) model. A new MSBS was designed and has been built for more advanced study on magnetic levitation technology.

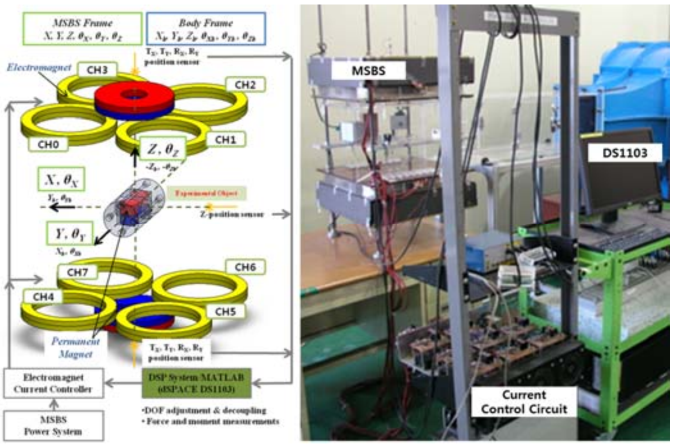

Figure 2. Configuration of the Magnetic Suspension and Balance System

2 WIND TUNNEL TESTS USING MSBS

2.1 Configuration of MSBS

An MSBS, which is developed by Y. Kawamura of FIT, was employed to measure aerodynamic forces and moments acting on various experimental models. Figure 2 shows the configuration diagram of the MSBS. The MSBS can levitate an experimental model using magnetic forces and moments. The most of the weight of an experimental model is countervailed by two large permanent magnets. The eight electromagnets control the position and attitude of the model with measurement information comes from optical sensor system. A DS1103 of dSPACE™ is applied as a hardware for imbedding position and attitude controller. Eight channels of DA converters receive the optical sensor signals and eight channels of AD converters send control commands for each electromagnet. The imbedded controller generates control commands for the electromagnets in order to make all states of the model stable. The external forces acting on the model can be measured by detecting extra electric current for electromagnets [5]. The MSBS has a test section of 33cm×40cm and is installed around 30cm×30cm low speed wind tunnel of which flow speed range is from 0m/s to 30m/s.

2.2 Dynamic calibration

In order to measure external forces during experiments, MSBS also needs to be calibrated like other types of balances. Typical balances are generally calibrated through static method so that the relationship between known forces applied on the balance and electric signals is figured out through static experiment with pulleys and stings. However, static calibration method accompanies very complicated and laborious preparation process during multi-axis calibration because static method can be applied only with calibration jigs and various known forces for each degree of freedom. If the advantage of MSBS as non-contact type actuator is fully made use of, the MSBS can be calibrated through dynamic method.

The equation of motion of an experimental model levitated by the MSBS can be expressed as

$$m_i \ddot{x}_{i,t} = F_{i_{MSBS},t} + F_{i_{Aero},t} \tag{1}$$

where i represents each degree of freedom (X, Y, Z, θ_X, θ_Y, θ_Z) and t is time. m_i is mass or mass moment of inertia of the model. $x_{i,t}$ is position or attitude of the model for i-th degree of freedom at time t, measured by the optical sensor system. $F_{i_{Aero},t}$ and $F_{i_{MSBS},t}$ are external aerodynamic forces or moments and magnetic forces or moments acting on the model, respectively. During dynamic calibration, wind tunnel is turned off so that only magnetic forces and moments, which are proportional to each control command for each degree of freedom, are acting on the model. Therefore the equation of motion of the model can be written as follows.

$$m_i \ddot{x}_{i,t} = F_{i_{MSBS},t} = K_i U_{i,t} \tag{2}$$

$U_{i,t}$ represents control command for i th degree of freedom at time t so that proportional constant, K_i, is the only unknown in Equation 2. If the position or attitude of the model is excited, the proportional constant can be obtained from the relationship between control command and inertial force or moment. Figure 3 shows control command

and position of a cylinder model in X direction. The cylinder model is demanded to be excited as sinusoidal motion so that the control command as shown in Figure 3 was generated to excite X-directional position of the model. Because signals are not identical to sinusoidal signals, several dynamic tests were repeated for various amplitudes and the proportional constant was obtained through statistical method. Same procedure was repeated for other degree of freedom of the cylinder model in order to complete calibration process. The dynamic calibration method is also applied to a finite wing model and an MAV model.

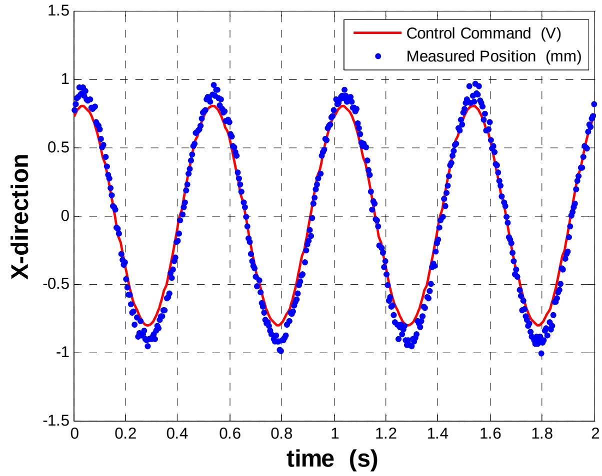

Figure 3. Sinusoidal motion of the model for dynamic calibration in X-direction

2.3 *Results of wind tunnel tests*

With the results of dynamic calibration, static aerodynamic forces and moments acting on several experimental models were measured during wind tunnel tests using MSBS. For static wind tunnel tests, inertial forces and moments do not exist so that the aerodynamic forces or moments acting on an experimental model can be obtained with following equation.

$$F_{i_{Aero},t} = m_i \ddot{x}_{i,t} - F_{i_{MSBS},t} = -F_{i_{MSBS},t} = -K_i U_{i,t} \quad (3)$$

The drag coefficients of a cylinder model were measured with respect to Reynolds number as shown in Figure 4. The fineness ratio of the cylinder model was 2 and the drag coefficients of the model converged to 0.85, which value is generally known drag coefficient of cylinder with that fineness ratio [13], as Reynolds number increases. The aerodynamic coefficients of a finite wing model were measured for various angles of attack. Meanwhile, the aerodynamic coefficients of Micro Air Vehicle (MAV) model were successfully measured for various angles of attack and elevator deflection angles. The MSBS was also employed to design flight controllers of the MAV model [6 - 8].

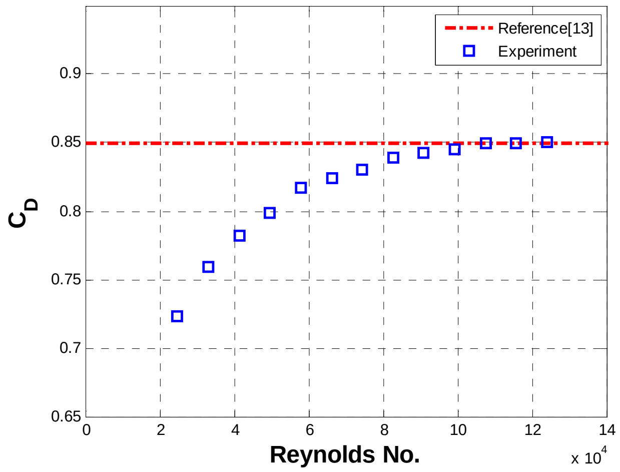

Figure 4. Drag coefficients of a cylinder model, L/D = 2

3 DEVELOPMENT OF NEW MSBS

3.1 *Current control circuit*

For more advanced study on magnetic levitation technology, a new MSBS was designed and has been built up to now. MSBS controls the position and attitude of an experimental model using magnetic forces and moments generated by electromagnets. These magnetic forces and moments are proportional to electric currents for each electromagnet and push-pull power supply is required to send currents to electromagnets accordingly. Figure 5 shows the electromagnet for the new MSBS and Figure 6 shows the push-pull power supply developed in KAIST.

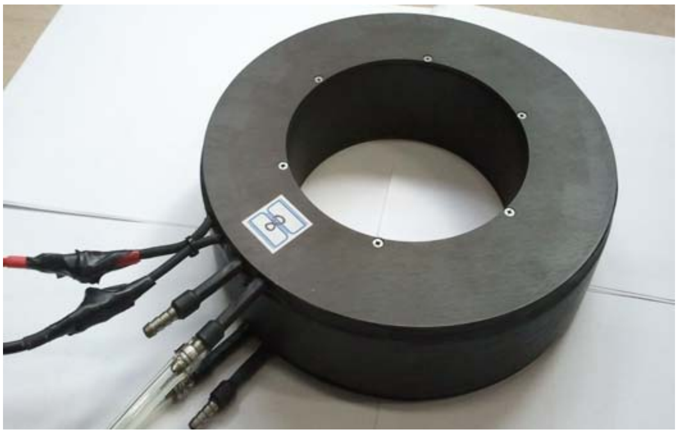

Figure 5. Electromagnet for position and attitude control

Inner and outer diameters of the electromagnet are 200mm and 128mm, respectively. Thickness of the electromagnet is 40mm and the number of turns is 317. The push-pull power supply can supply electric current of ±10A for each electromagnet of MSBS. The magnetic fields generated by electromagnets are proportional to the electric currents and magnetic forces and moments induced from the magnetic fields act on the experimental body, which is magnetized or has small permanent magnets inside, to control the position and attitude.

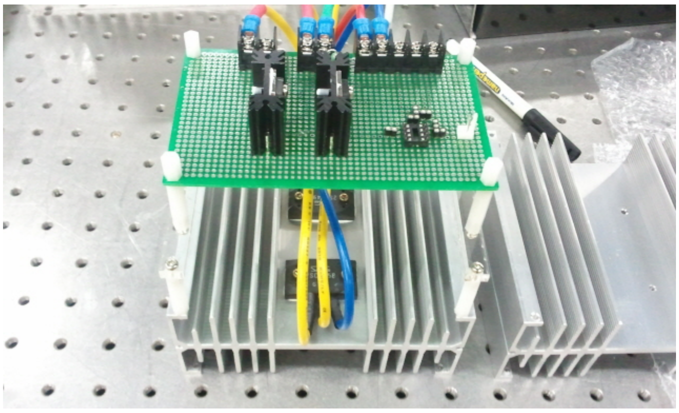

Figure 6. Push-pull power supply for electromagnet

3.2 Optical measurement system

Position and attitude of the experimental model at the test section of MSBS should be measured in order to control the motion of the model. In this study, an optical measurement system was tested to measure the position and attitude of the model without any mechanical contact. The system is composed of three optical sets and Figure 7 shows the light path of the optical set.

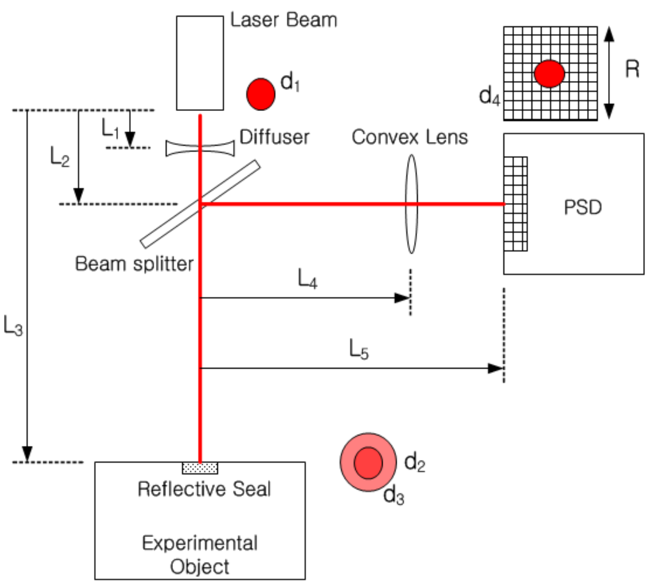

Figure 7. Light path of the optical measurement system

Laser beam, came from a laser source, is spread by diffuser and passes the beam splitter. The laser beam is reflected by the reflective seal, which is attached on the surface of an experimental model. Then beam splitter changes the direction of the reflected laser beam so that the laser beam can be aimed to a Position Sensitive Diode (PSD) sensor. With this optical measurement system, two dimensional motions of the reflective seal can be measured so that the movement of the experimental model can be eventually obtained. Each of the three optical measurement systems measures two dimensional motions of each reflective seal, which is attached on the upper, lower, and side surface of the model. The position and attitude of the experimental model can be measured with combinations of the six measurement values from the optical measurement system.

4 CONCLUSIONS

In order to measure aerodynamic forces and moments acting on an experimental model or observe the air flow around the model, wind tunnel tests are frequently used. The aerodynamic model should be fixed at the center of the test section of the wind tunnel during the tests and mechanical supports are generally employed to hold the model and measure the aerodynamic forces acting on the model. However, these mechanical supports generate disturbances to the air flow around the aerodynamic body and this support interference problem decreases accuracy of the experimental results. MSBS can provide one of ideal solutions for these support interference problems. MSBS can levitate a magnetized object at the center of the test section with magnetic levitation forces and moments produced by several electromagnets around the model. Therefore an aerodynamic model can be located at the center of the test section without any mechanical support during wind tunnel test so that support interference can be eliminated. In addition, the aerodynamic forces and moments acting on the model can be measured by detecting the electric currents flowing through each electromagnet. In this study, dynamic calibration was performed for several experimental models so that the aerodynamic forces and moments acting on the models could be measured during wind tunnel tests while eliminating support interferences. Push-pull power supply and optical measurement system was developed for the new MSBS designed for more advanced work.

5 ACKNOWLEDGEMENT

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