

Measurement of Mass of Spherical Model by Magnetic Suspension and Balance System

Riho NAKAMURA* and Hiroyuki FUJIWARA*

*Department of Mechanical Engineers, National Defense Academy

1-10-20 Hashirimizu, Yokosuka-shi, Kanagawa 239-0811, Japan

E-mail: ed24008@nda.ac.jp

Abstract

This paper aims to verify the feasibility of measuring the mass of a spherical model using a Magnetic Suspension and Balance System (MSBS). The MSBS was developed to support models and conduct wind tunnel tests without airflow interference. The MSBS levitates the model by using magnetic force. Therefore, physical support devices are unnecessary during wind tunnel tests. In this study, a spherical model levitated in the air using the MSBS was excited at a constant frequency. The mass of the spherical model was calculated based on the relationship between the applied external force, model amplitude, natural frequency, and excitation frequency during oscillation. The applied external force was electromagnetic force, and it was determined based on the relationship between the electromagnetic force and the distance between permanent magnets positioned at the top of the MSBS and inside the spherical model. The amplitude was calculated using the sensor voltage and the width of the laser. Additionally, the natural frequency was determined based on the bode plot of the open loop transfer function. Consequently, this method confirmed the feasibility of measuring the mass of the model using the MSBS. In further study, the model will be levitated in water using the MSBS and excited to experimentally measure the added mass.

Keywords : Magnetic Suspension and Balance System, Added mass, Electromagnetic force, Magnetic levitation, Open loop transfer function

1. Introduction

When evaluating the aerodynamic performance of an aircraft, experiments are often conducted using a reduced-scale model placed in a wind tunnel. In such cases, the model is typically supported by struts. The struts prevent changes in the posture of the model due to gravity and external force from the surrounding gas, maintaining the position and posture of the model (The Institute of Electrical Engineering of Japan, 1993). However, airflow interference caused by the struts decreases the accuracy of the experimental results. To solve this problem, a Magnetic Suspension and Balance System (MSBS) was developed. The MSBS levitates the model in the air using magnetic force during wind tunnel tests. Therefore, accurate measurements of forces and moments acting on the model are considered feasible, because physical support devices are unnecessary during wind tunnel tests. Additionally, various studies using the MSBS are being conducted. The main feature of the MSBS is that it can control the position and motion of the model by adjusting magnetic force. Thus, we propose that added mass in water can be determined through experiments in which the MSBS is used to levitate the model in water while inducing oscillations. Added mass refers to the apparent increase in mass when the model moves with acceleration in water. This is essential for predicting seismic responses in the design of marine structures.

The purpose of this study is to confirm the feasibility of measuring the mass of a spherical model in the air using the MSBS and to measure added mass of the model in water using the MSBS after this study. This paper discusses a method for measuring the mass of the model and presents experimental results.

2. Experiment apparatus

Figure 1 shows the appearance of the MSBS used in this study. The MSBS consisted of a control computer, a current controller, a permanent magnet, a coil, and a laser sensor. The permanent magnet has an outer diameter of 150 mm, an inner diameter of 50 mm, and a thickness of 25 mm. The coil has an outer diameter of 180 mm, an inner diameter of 140 mm, a thickness of 25 mm, and 225 turns. Figure 2 shows a block diagram. This MSBS was based on a device developed by the Fukuoka Institute of Technology (Y. Kawamura et al., 2004). Most of the gravity acting on the model is counterbalanced by the magnetic force generated by two permanent magnets; one positioned at the top of the MSBS and the other inside the model. Consequently, the MSBS enables the model to levitate in the air without requiring a large current. Furthermore, the floating control is operated with a single degree of freedom. When the model moves vertically, the sensor transmits a signal to the controller, inducing an electric current through the coil. This current flows in such a way that the generated force acts in the direction opposite the displacement of the model.

Figure 3 shows the model used in this study. This spherical model, made of Duracon®, has a diameter of 80 mm and a mass of 690 g. This model contains inside a cylindrical permanent magnet with a diameter of 40 mm and a thickness of 40 mm.

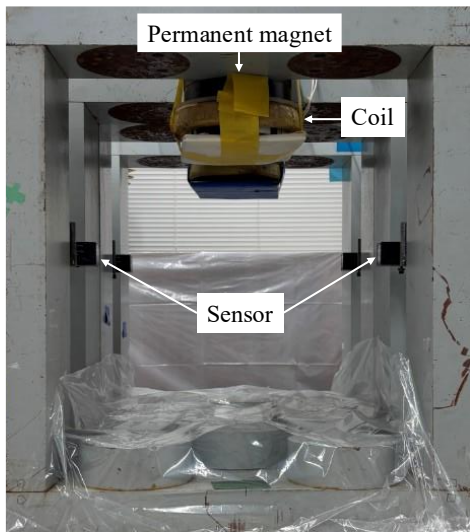


Fig. 1 A appearance of the Magnetic Suspension and Balance System (MSBS).

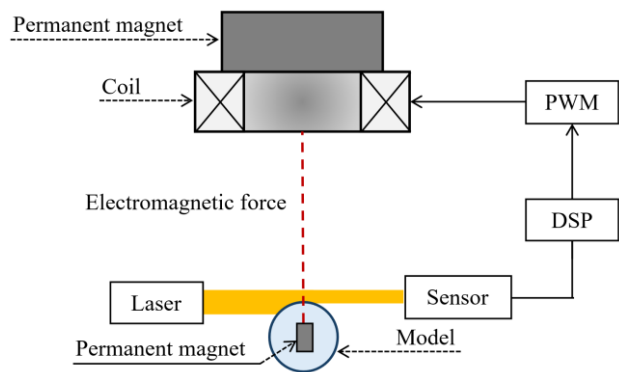


Fig. 2 Block diagram for the simulation of a single degree of freedom control of the MSBS.

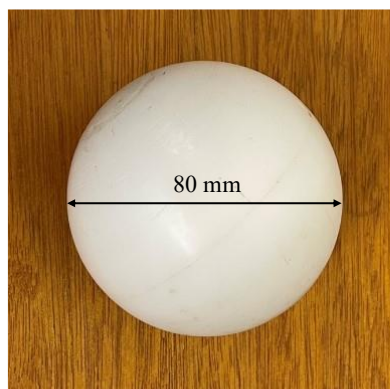


Fig. 3 Spherical model with diameter of 80 mm used in this study.

3. Experimental method

The model was levitated using the MSBS and excited at a constant frequency while measuring the mass of the spherical model. Determination of the relationship between the current flowing through the coil and electromagnetic

force is necessary, because the amplitude during oscillation is required for calculating the mass of the model. Therefore, calibration of the electromagnetic force is necessary.

3.1 Calibration of electromagnetic force

When the gravity acting on the model and magnetic force of the permanent magnets are balanced, the electromagnet does not exert any force on the levitated model using the MSBS. Therefore, the current flowing through the coil becomes 0 A. First, the current flowing through the coil was measured while varying the levitated position of the model. Moreover, the distance between permanent magnets positioned at the top of the MSBS and inside the spherical model was calculated when the current flowing through the coil was 0 A. This distance is denoted as z_p . Additionally, the distance z_p was also calculated when the current through the coil was -2 A, -1 A, 1 A, and 2 A. Subsequently, the same measurement was conducted with the model having various weights added.

The relationship between the distance z_p and the electromagnetic force can be calculated using the following equation.

$$F_e = i \frac{2.71 \times z_p \times 10^{-3}}{(0.08^2 + (\frac{z_p}{1000})^2)^{\frac{5}{2}}} \times h \times 0.02 \times \pi \times 0.04 \quad (1)$$

where F_e represents electromagnetic force, i is current through the coil, μ_0 is vacuum permeability, and h is a correction value. Figure 3 shows the measured values of the relationship between the distance z_p and the electromagnetic force, as well as the results calculated from Eq. (1). As a result of adjusting to align the graphs as illustrated Fig. 3, the correction value became 1.7.

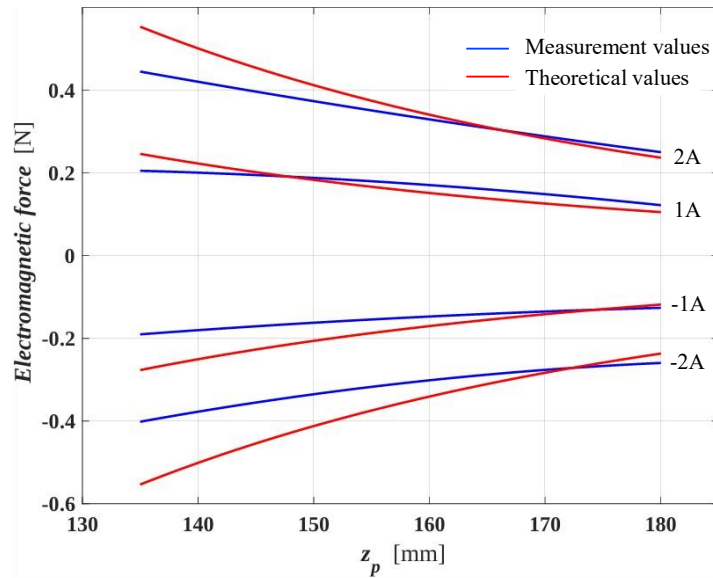


Fig. 3 Relationship between electromagnetic force and distance. Theoretical value calculated using Eq. (1) and the measured value are plotted with solid red and blue lines, respectively.

3.2 Method for measuring mass of the model

In this study, the spherical model was floated in the air using MSBS and excited at various frequencies. The amplitude of a single degree of freedom under the forced oscillation of an external force can be calculated using the following equation.

$$a = \frac{F}{m \times \omega_n^2 \sqrt{\left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\zeta \frac{\omega}{\omega_n}\right)^2}} \quad (2)$$

where a is amplitude, m is mass of the spherical model, ω is excitation angular frequency, ω_n is natural angular frequency, and ζ is damping ratio. The amplitude can also be calculated using the following equation.

$$a = \frac{V'_{\max} - V'_{\min}}{(V_{\max} - V_{\min}) \times 2} \times 15 \quad (3)$$

where V_{\max} and V_{\min} represent the maximum and minimum voltage of the sensor, V'_{\max} and V'_{\min} are their values during the excitation of the spherical model, and 15 represents the width of the laser.

3.3 Method for measuring natural frequency

To calculate the mass of the spherical model from Eq. (2), the natural angular frequency and the damping ratio need to be determined. Therefore, the spherical model was levitated using the MSBS, as shown in Fig. 4, and excited with a sweep signal. The gain-crossover frequency f_z and the phase lead φ were determined based on the bode plot of the open loop transfer function. Figure 5 shows the bode plot. As shown in Fig. 5, the gain-crossover frequency was 2.33 Hz, and the phase lead was 12.19°. The damping ratio can be derived from the phase lead, which was 0.108. In this study, the gain-crossover frequency was assumed to represent the natural frequency because the damping ratio was small. Therefore, the natural frequency was 2.33 Hz.

Ultimately, the mass of the spherical model was determined by substituting the values obtained using the method explained above into Eq. (2) and solving for m .

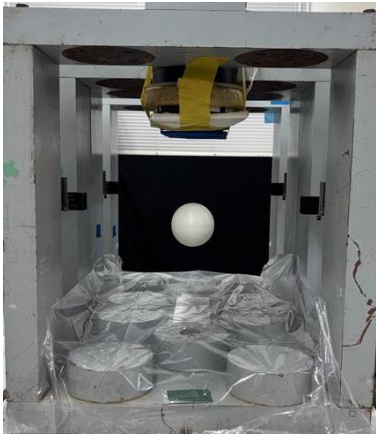


Fig. 4 Spherical model levitated by the MSBS.

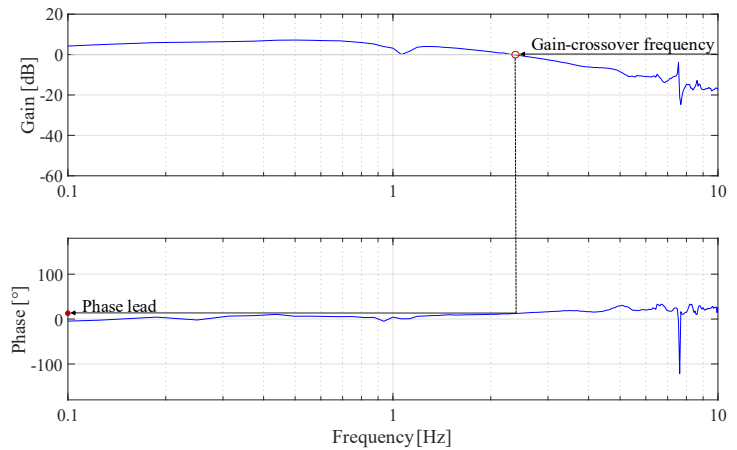


Fig. 5 Bode plot. The Bode plot was the open-loop transfer function of control system. From this plot, the gain-crossover frequency and the phase lead were measured.

4. Result

The measurement results of the mass and their errors at each excitation frequency are summarized in Table 1. The table indicates that the error was significant when the spherical model was excited at the natural frequency. This may be due to a substantial increase in amplitude caused by the model's resonance. Conversely, the measurement results at frequencies other than the natural frequency had an error within 10%. Therefore, this method is considered feasible for

measuring the mass of the model when the model is excited at any frequency other than the natural frequency.

Table 1 The measurement values and errors.

Excitation frequency [Hz]	Measurement value [g]	Error [%]
2.33	1038	50.5
3	733.8	6.35
4	655.1	5.05
5	628.9	8.85

5. Concluding remarks

In this study, the mass of a spherical model was measured using the MSBS. Despite the occurrence of errors, the experimental results confirm the feasibility of measuring the mass of the model using the MSBS.

In future research, the mass of the spherical model will be measured using a different method and the result will be compared with the accuracy of the method used in this study. Subsequently, the added mass in water will be measured using the MSBS with the method that demonstrates better accuracy. The theoretical values of added mass are listed in the Handbook of Mechanical Engineering for certain model shapes. Initially, the added mass of models for the spherical model and shapes will be determined with known theoretical formulas. Subsequently, measurement of the added mass will be conducted for models with arbitrary shapes.

References

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