# Wind Tunnel Experiment of Bluff Body Aerodynamic Models Using a New Type of Magnetic Suspension and Balance System

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*We have measured drag coefficients of a sphere and a circular cylindrical aerodynamic model using a five axes and a six axes control magnetic suspension and balance system (MSBS) developed by us. This MSBS has the characteristics of large aperture relative to the weight, light weight, and small electric power consumption in comparison with the conventional ones. We had good agreements between the measured values of the drag coefficient and the values appearing in the common aerodynamic handbook or textbook. We also succeeded in measuring the aerodynamic influence of a supporting rod of the aerodynamic models making use of the characteristics of the MSBS. Conventionally, the MSBS can be used only in large scale laboratories because the size, weight, and electric power consumption are large. We think that successful measurements of various aerodynamic characteristics using this type of MSBS will stimulate the introduction of it into the wind tunnel experiments in small scale laboratories.* [DOI: 10.1115/1.4024793]

*Keywords: magnetic suspension, magnetic levitation, wind tunnel, electric power saving, light weight, control, bluff body*

## 1 Introduction

A magnetic suspension and balance system (MSBS) is one of the experimental systems among the magnetic levitation technologies [1–3]. Using this system, it is possible to sustain aerodynamic models stationary in a wind tunnel without a supporting rod. It is also possible to measure the aerodynamic forces and torques applied to the models precisely through the magnetic forces between the permanent magnets installed in the model and the electric magnets surrounding them. The MSBSs have been studied in many laboratories, but most of them were the large scale laboratories belonging to big institutes. Probably the reason why it has not been used in small laboratories is that the MSBS is an experimental setup of large scale, heavy weight, and large electric power.

We have developed a new type of MSBS having the characteristics of large aperture, low weight, and low electric energy consumption [4]. Using this MSBS, we measured drag coefficients of a sphere and a circular cylindrical aerodynamic model in order to confirm the performance of our MSBS. We have had good agreements between the measured values of drag coefficients of the aerodynamic models and those appearing in the common aerodynamic handbook or textbook. We think that these experimental results will stimulate the popularization of the MSBS in small laboratories.

This MSBS has also been used for the experiment of moving models. Namely, the measurement of the aerodynamic characteristics of a flapping wing sustained and driven by the MSBS have been successfully performed [5].

## 2 Five Axes MSBS Experiment

**2.1 Experimental System.** Figure 1 shows the experimental setup of a five axes control MSBS. The system is composed of a personal computer (PC), current control circuits, eight electric magnets, a pair of large size strong permanent magnets, and an optical detection system of the positions and the attitudes of the model. In the aerodynamic model, a cylindrical permanent magnet (diameter: 35 mm, length: 40 mm, residual magnetic flux density: 1.35 T, material: neodymium magnet) is installed to generate the magnetic force.

The gravitational force of the model is compensated by the magnetic force generated by a pair of permanent magnets; therefore it is not necessary to generate it by electric magnets, which reduces the consumption of electric power. This method has

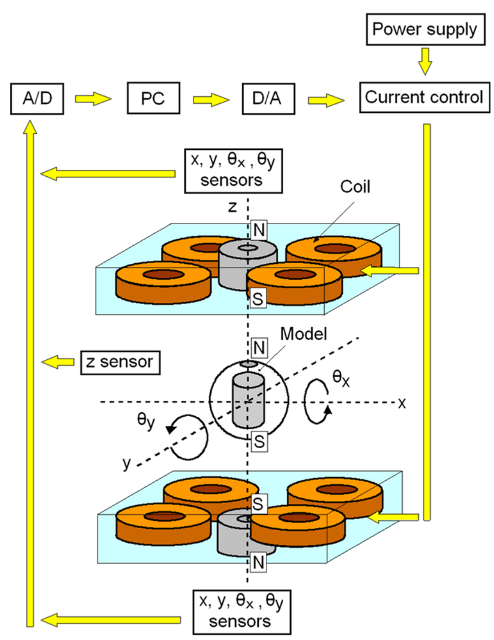


**Fig. 1 Experimental system of the five axes MSBS**

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Table 1 **Dynamic ranges and the measurement accuracies of the five axes control MSBS (for the averaged measurement of 1024 times)**

| Control axis | $z$ | $x$ | $y$ | $\theta_x$ | $\theta_y$ |
|---|---|---|---|---|---|
| Range of measurement | ±0.6 N | ±0.8 N | ±0.8 N | ±0.06 Nm | ±0.06 Nm |
| $\sigma_n$ | 0.0014 N | 0.00076 N | 0.0016 N | 0.00028 Nm | 0.00024 Nm |
| Accuracy (% full scale) | 0.24% | 0.10% | 0.20% | 0.47% | 0.40% |

already been used in the spinning rotor vacuum gauge to sustain small iron balls spinning in vacuum [6,7].

In the conventional MSBS, iron yokes have been used to construct magnetic circuits which reduce the leakage of the magnetic flux and make the magnetic force stronger [1–3]. The test section, the weight, and the electric power consumption were 60 cm × 60 cm (at maximum), several tons, and several ten kW, respectively, in the conventional system. We have tried not to use the iron yokes to reduce the total weight and make the size smaller. The test section, the weight, and the electric power consumption of our MSBS are 400 mm (width) × 360 mm (height), 50 kg, and 1.5 kW (at maximum), respectively.

In the conventional MSBS the distribution of the electric magnets has been designed in accordance with the horizontally long models, such as airplanes and rockets; therefore the magnetic axis was taken in the horizontal direction. In contrast with it, the magnetic axis was taken in the vertical direction in this system, which is suitable for the aerodynamic models of a bluff body type, such as a sphere model.

In Table 1 the dynamic ranges and the measurement accuracies of this MSBS are summarized for the averaged measurement of 1024 times. Calibration of the wind velocity was performed carefully using a Pitot tube anemometer. The drag force is calibrated by conventional method (using weights, strings, and pulleys). The details of the operation characteristics of this MSBS system will be described in another article [4].

In this configuration of the magnetic field, it is possible to spin the model around the vertical axis at a revolution velocity of several tens of rounds per second; for example, by blowing air stream to the model. It is also one of the characteristics of this new type of MSBS.

**2.2 Wind Tunnel Experiments.** Figure 2 shows the experimental setup for the wind tunnel experiment using the five axes

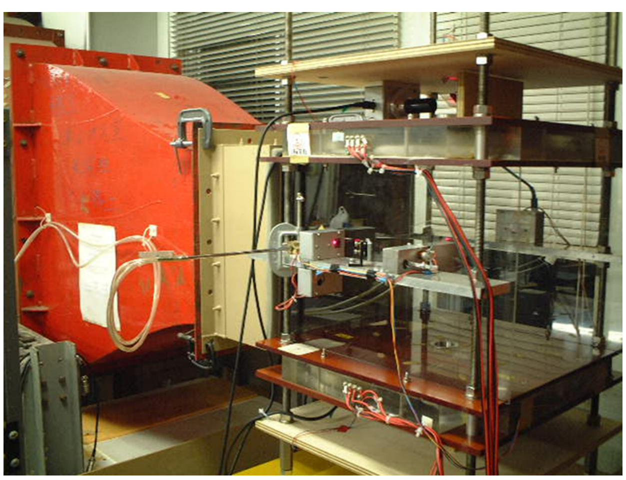

**Fig. 2 Five axes MSBS set at the test section of a wind tunnel**

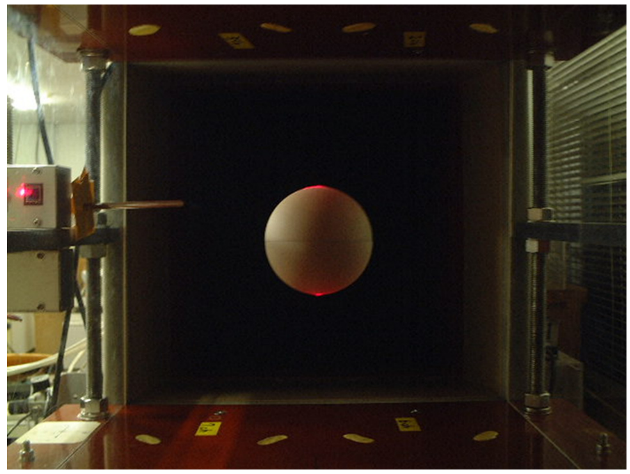

**Fig. 3 Levitation of a sphere model having a diameter of 70 mm in the five axes MSBS**

MSBS. The uniformity of the wind velocity and the intensity of turbulence of the wind tunnel are ±1% and 0.1%, respectively [8]. The cross section of the test section is 400 mm (width) × 360 mm (height).

Figure 3 shows the levitation of a sphere model having a diameter of 70 mm. The weight is 383 g. The size and material of the magnet are the same as those used in the calibration experiments.

The diameter of the sphere was chosen to realize the experiment of the aerodynamic characteristics of baseball balls. Namely, the baseball ball model can be obtained by covering the sphere model by two leathers of the baseball ball and sewing them up with strings. By blowing the air jet stream to the sphere, the rotation rate of more than 50 rps was easily obtained and was stable. This facility was designed for the aerodynamic experiments of the knuckle ball [9].

Figure 4 shows the coil currents for the five axes as a function of the wind velocity. It can be seen that the current of the $y$ axis increases almost proportional to the square of the velocity. The coil current is proportional to the drag; therefore this result shows that the drag forces are almost proportional to the square of the wind velocity.

Figure 5 shows the drag coefficients of this sphere model as a function of Reynolds number using open squares, which is calculated using the data shown in Fig. 4. For comparison, the data from the mechanical engineering handbook are shown using open

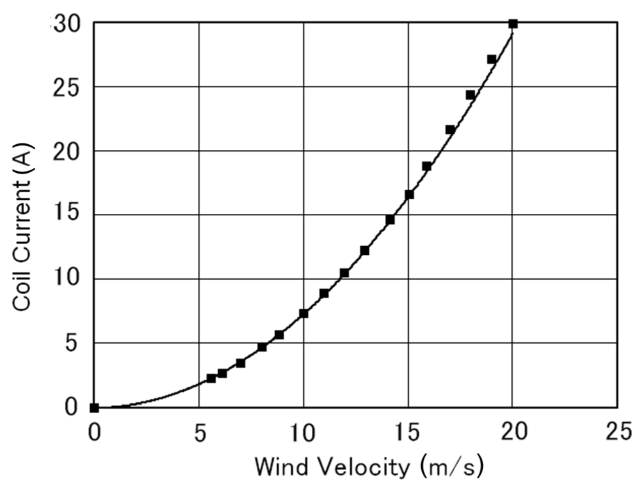


**Fig. 4 Coil current for $y$ axes as a function of the wind velocity in the measurement of the drag coefficient of the sphere aerodynamic model using the five axes MSBA**

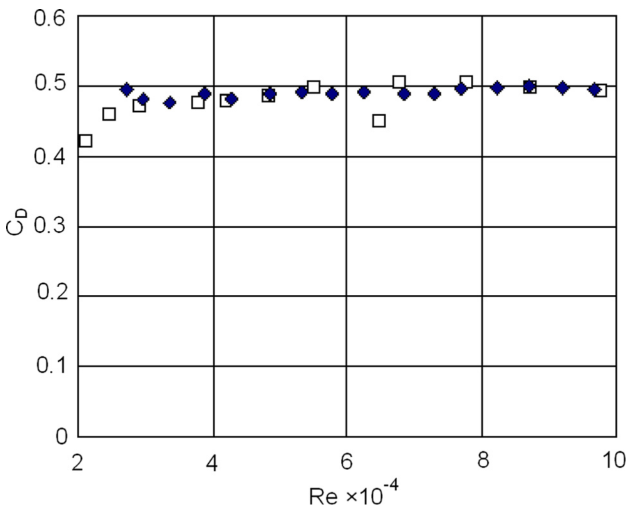


**Fig. 5 Drag coefficients of the sphere model as a function of Reynolds number measured by the five axes MSBS. (Solid squares: experimental results by the MSBS, open squares: data from JSME handbook [10].)**

squares [10]. They are in good agreement with each other in a wide range of Reynolds numbers.

The influence of the supporting rod to the measurement of the aerodynamic forces is the important factor for the preciseness of the measurement in the wind tunnel experiments. In this experiment the influence of the supporting rod to the drag force was measured by making use of the advantage of the MSBS.

A pseudo supporting rod with a diameter of 6 mm is placed in the same position, where the real supporting rod is placed in case of the conventional mechanical supporting of the model as shown in Fig. 6. There is a small gap (1 mm) between one end of the rod and the model; therefore they do not touch with each other. The gap length is much smaller than the diameter of the rod, and the stream lines are considered not to penetrate into the gap. Therefore, the stream lines around the model and the rod are considered to be almost the same as those appearing in the experiment using a real supporting rod. Under such a condition the measurement of the drag coefficient was performed. In the next step this pseudo supporting rod is removed and the measurement was again performed. The difference between these two results is considered to be the effect induced by the existence of the supporting rod.

Figure 7 shows the drag coefficients with and without the pseudo supporting rod as a function of the Reynolds number. The

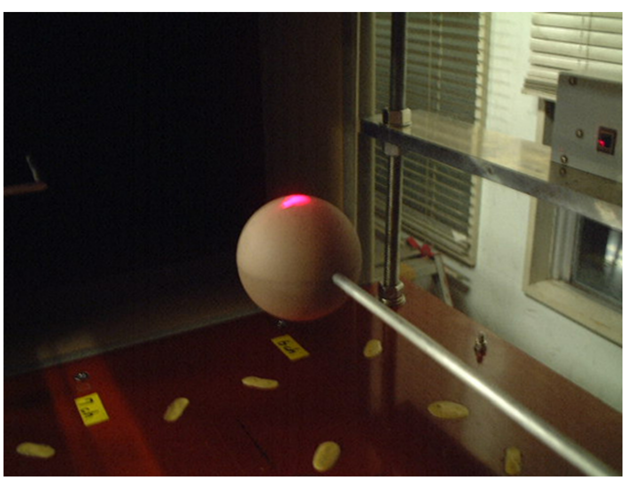

**Fig. 6 Pseudo supporting rod and the levitated sphere model. There is a short gap between the end of the rod and the sphere model.**

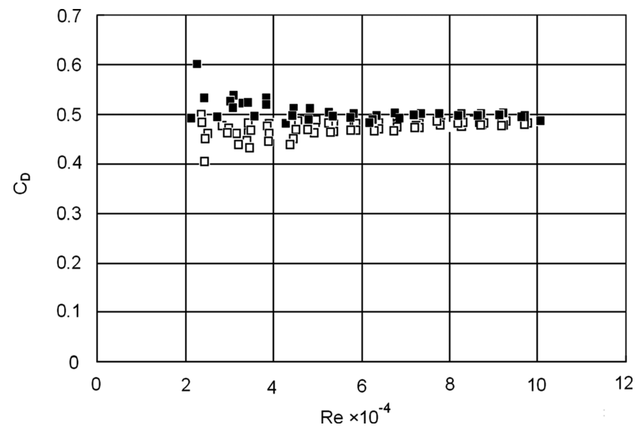


**Fig. 7 Drag coefficients of a sphere model levitated by the MSBS with and without the pseudo supporting rod as a function of the Reynolds number. (Solid squares: without pseudo support bar, open squares: with pseudo supporting rod.)**

reduction of the drag coefficient with the existence of the pseudo supporting rod was about 3%. In general, the existence of the supporting rod in the down stream of the model decreases the drag coefficient because the decrease in the volume of the down stream made by the existence of the rod suppresses the vortex shedding. Our experimental result was in accordance with such a general tendency, and has quantitatively shown the existence of the influence by the supporting rod.

## 3 Six Axes MSBS Experiment

**3.1 Experimental System.** Figure 8 shows the experimental system of the six axes control MSBS. The differences from that for the five axes control are the following three. The first one is the addition of the optical detection system for the rotation around the $z$ axis ($\theta_z$). The second one is the addition of the control algorithm for the rotation around the $z$ axis ($\theta_z$). The third one is modification in the design of the magnets in the model. Namely, a pair of permanent magnets was set in the model to generate the torque around the $z$ axis ($\theta_z$).

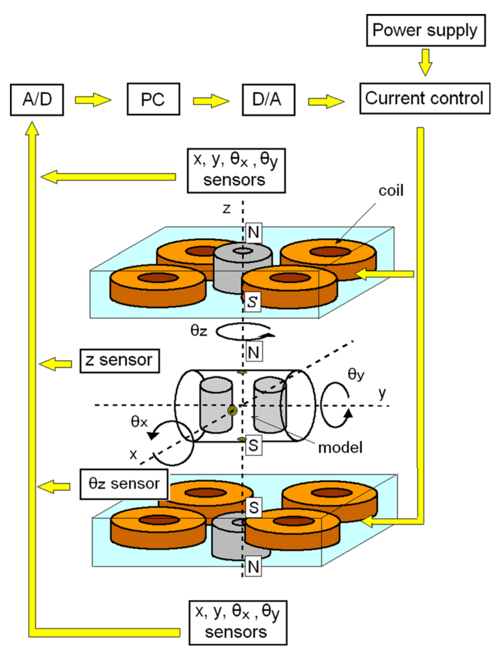


**Fig. 8 Experimental system of the six axes MSBS**

Table 2 Dynamic ranges and the measurement accuracies of the six axes control MSBS (for the averaged measurement of 1024 times)

| Control axis | $x$ | $y$ | $z$ | $\theta_x$ | $\theta_y$ | $\theta_z$ |
|---|---|---|---|---|---|---|
| Range of measurement | ±2.16 N | ±2.03 N | ±1.22 N | ±0.14 Nm | ±0.22 Nm | ±0.02 Nm |
| $\sigma_n$ | 0.0031 N | 0.005 N | 0.007 N | 0.0005 Nm | 0.0001 Nm | 0.0003 Nm |
| Accuracy (% full scale) | 0.1% | 0.3% | 0.5% | 0.4% | 0.05% | 2% |

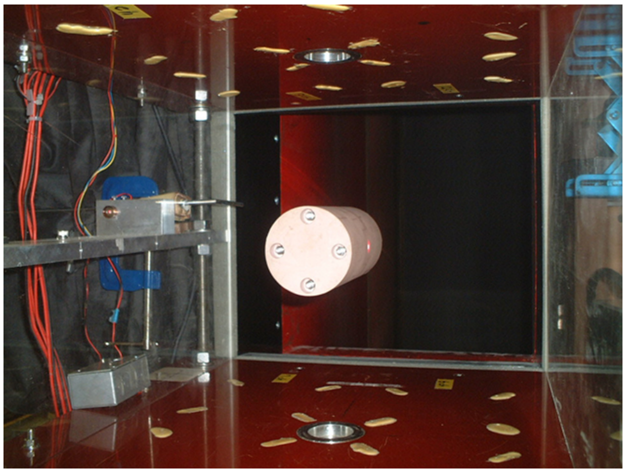

**Fig. 9 Levitation of a cylindrical model with a diameter of 70 mm and a length of 140 mm in the five axes MSBS**

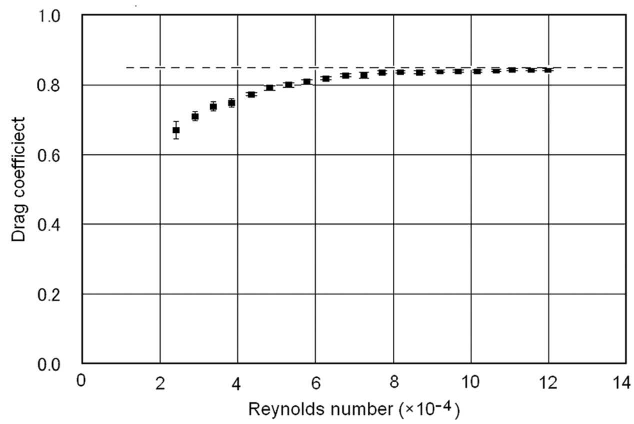


**Fig. 11 Drag coefficients of the cylindrical model as a function of Reynolds number measured by the six axis MSBS. Error bars represent the standard deviation of five data. Dashed line is the drag coefficient of the cylinder having the same ratio for Reynolds numbers >$10^4$ [11].**

In Table 2 the dynamic ranges and the measurement accuracies of this MSBS for the averaged measurement of 1024 times are summarized. The drag force is calibrated by the conventional method (using weights, strings, and pulleys). The details of the operation characteristics of this MSBS system will be described in another article [4].

**3.2 Wind Tunnel Experiments.** Figure 9 shows the levitation of a cylindrical model with a diameter of 70 mm and a length of 140 mm in the six axes MSBS. The direction of the wind is the axis of the cylinder ($y$ axis).

Figure 10 shows the drag of the cylindrical model to the $y$ direction as a function of the wind velocity measured by the six axes MSBS. It can be seen that the drag to the $y$ axis increases almost proportional to the square of the velocity.

Figure 11 shows the drag coefficients of this cylinder model as a function of Reynolds number, which is calculated using the data shown in Fig. 10. Error bars represent the standard deviation of five data. According to a reliable textbook in the field of fluid dynamics [11], it is 0.85 for Reynolds numbers larger than $10^4$, which is in very good agreement with our results. This experimental result not only shows the accuracy of our MSBS, but also enhances the reliability of the value of the drag coefficient (0.85) in the textbook [11].

The scatters of the data in Figs. 5, 7, and 11, are not only determined by the accuracy of the MSBS, but also determined by the dynamic fluctuations of the flow in the measurement area of the wind tunnel. Therefore, the scatters of the data generally become larger than the accuracy of the MSBS determined by the static calibration. Especially, at low Reynolds number, the aerodynamic forces become relatively small, and the scatters become larger.

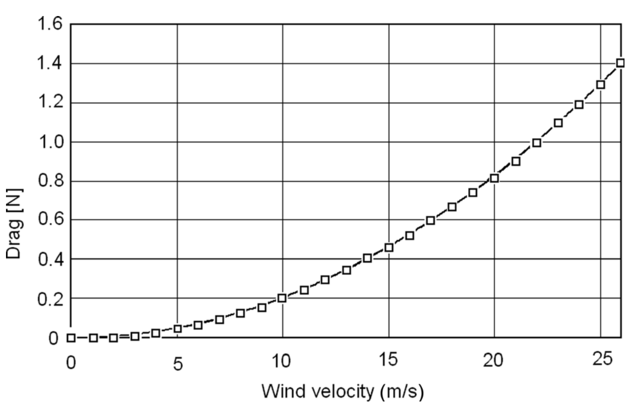


**Fig. 10 Drag of the cylindrical model to the *y* direction measured by the six axes MSBS as a function of the wind velocity**

## 4 Summary

We have measured drag coefficients of a sphere and a circular cylindrical aerodynamic model using five axes and six axes control MSBSs developed by us. This MSBS has the characteristics of light weight and small electric energy consumption in comparison with the conventional ones. The drag coefficients measured here were in good agreements with the values appearing in the common aerodynamic handbooks. We also succeeded in measuring the aerodynamic influence of a supporting rod of the aerodynamic modes making use of the characteristics of the MSBS.

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