Proposal of Surface-Rotating Ball for Wind-Tunnel Using Magnetic Suspension

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Abstract

A wind-tunnel system for a spinning ball has been proposed to measure aerodynamic forces acting on the body. In the proposed system, the ball is suspended and rotated by electromagnets. The forces are measured from the control signal for suspension. However, due to the non-uniformity of the magnetic fields, rotation around a horizontal axis suffered from drag torque caused by eddy currents induced in the surface of the ball. It led to high energy consumption in the electromagnets. In this work, a surface-rotation ball with an adjustable rotating axis is proposed and developed. The ball is suspended stably with various-attitude surface rotation.

1 Introduction

Magnetic suspension provides an ideal way of supporting a model for wind tunnel tests because there is no support interference problem arising with mechanical model-support (Boyden, Britcher, & Tcheng, 1985). The forces and moments to support the model are generated by electromagnets arranged outside the test section. In addition, aerodynamic forces acting on the model are estimated from the control current of the electromagnets.

Aerodynamics around a spinning body such as golf ball is still an intriguing topic in both academic and industrial fields. Although simulation-based analysis has been making very rapid progress, the details of the dynamics have not been clarified sufficiently. The main difficulty is that the target phenomenon is a complex mix of macro-scale and micro-scale dynamics. Therefore, ideal wind tunnel tests are required for more precise and reproducible observation. However, conventional wind tunnels using magnetic suspension were not designed to test a spinning body so that they lacked the function of rotating the body (Boyden, Britcher, & Tcheng, 1985) (Sawada, Suenaga, Suzuki, & Ikeda, 1994).

We have proposed a wind-tunnel system for spinning body to measure hydrodynamic forces acting on the body (Mizuno, Sakai, Ishino, & Takasaki, 2012) (Mizuno, Sakai, Takasaki, & Ishino, 2017). In the proposed system, the body is suspended and rotated by electromagnets. The forces acting on the body are measured from the control signal for suspension. An experimental apparatus with a 60×60 mm wind tunnel was fabricated which has eight electromagnets around a wind-tunnel and an optical displacement sensor for detecting the three-dimensional positions of the body. Stable suspension, three-dimensional positioning and rotation of the body were achieved (Mizuno, Sakai, Takasaki, & Ishino, 2017).

However, due to the non-uniformity of the magnetic fields, rotation around a horizontal axis suffered from drag torque caused by eddy currents induced in the surface of the ball. It led to high energy consumption in the electromagnets. It is obviously preferable that rotation around an arbitrary axis can be achieved.

In this work, a surface-rotating ball is proposed, designed and fabricated. In this ball, the surface spherical shell rotates while the enfolded structure including magnetic cores, a motor, its driver circuit and a battery does not rotate. Therefore, no drag torque due to induced eddy currents is generated. It is experimentally demonstrated that the ball is suspended stably with surface rotation.

2 Wind Tunnel for Spinning Body Using Magnetic Suspension

Figure 1 shows a photograph of the developed wind tunnel using magnetic suspension (Mizuno, Sakai, Takasaki, & Ishino, 2017). The size of the total system is $360 \times 1200 \times 440$ mm, approximately. It consists of a magnetic suspension mechanism, a three-axis displacement sensor, a controller and a wind-tunnel.

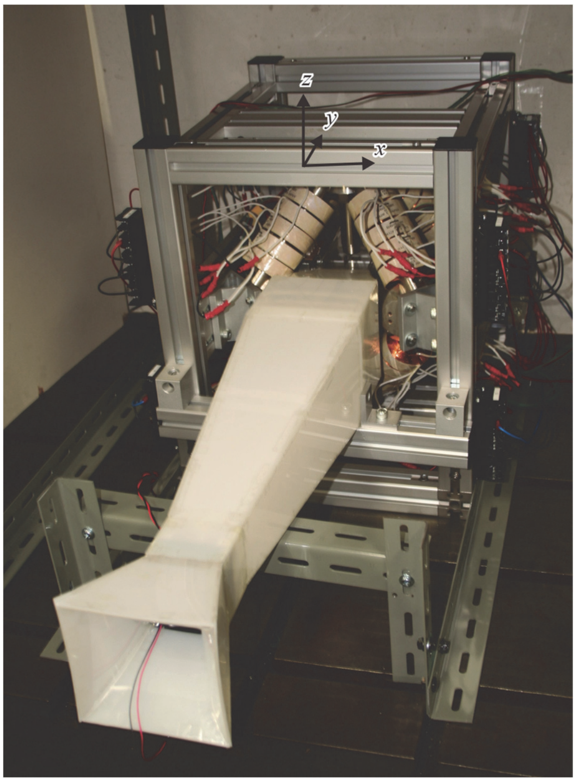


Figure 1: Picture of wind tunnel for spinning ball using magnetic suspension

2.1 Magnetic suspension mechanism

A schematic drawing of the mechanism for magnetic suspension is shown in Figure 2 where the nearest electromagnet is removed for a better view of the inside poles. The size is $244 \times 244 \times 296$ mm. The suspension system has eight electromagnets for controlling the three-dimensional position of a sphere body made of ferromagnetic material. Each electromagnet has five 300-turn coils. The impedance of the electromagnet can be adjusted by the connections of the coils. The distance of the poles are kept long enough for a 60×60 mm wind tunnel to be inserted.

2.2 Suspension object

The object was a steel ball with a diameter of 19mm and a mass of 28.4g. There are machined dimples on the surface to simulate a golf ball.

2.3 Sensor

The operation of an optical sensor detecting the three-dimensional positions of the object is illustrated in Figure 3. It combines a pair of unit with a LED (light source), four collecting lens and four phototransistors. It can detect the three-dimensional positions of the body in the full-differential mode. When the output of the phototransistor k $(k = 1, \cdots, 8)$ is denoted by S_k, the displacement in each direction is estimated from

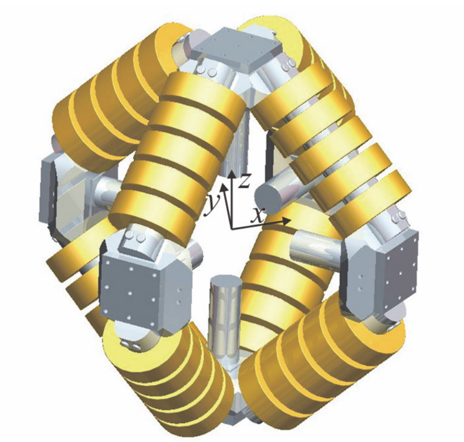


Figure 2: Schematic drawing of magnetic suspension mechanism

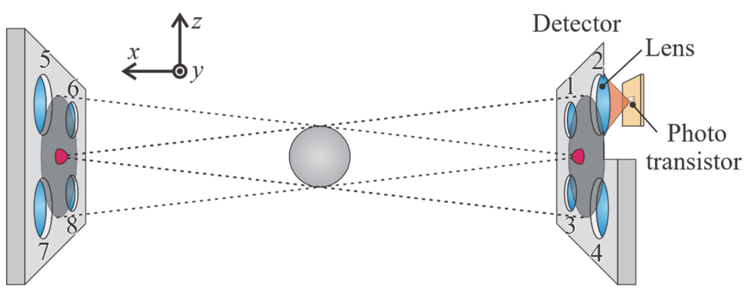


Figure 3: Operation of position sensor

$$
\begin{cases}
x - axis : (S_1 + S_2 + S_3 + S_4) - (S_5 + S_6 + S_7 + S_8) \\
y - axis : (S_2 + S_4 + S_5 + S_7) - (S_1 + S_3 + S_6 + S_8) \\
z - axis : (S_1 + S_2 + S_5 + S_6) - (S_3 + S_4 + S_7 + S_8)
\end{cases}
\quad (1)
$$

This sensor is expected to be superior in linearity and resolution, especially as to the *x*-direction, to the sensor used in the previous work (Mizuno, Furutachi, Ishino, & Takasaki, 2010) because the latter operates in a single mode in this direction.

2.4 Levitation and rotation

Stable suspension was achieved by applying PID control. Figure 4 shows the motions of the floater in the wind of 8 m/s in the *y*-direction. It is observed that the position of the body is kept stably whereas vibratory motions were induced by a wind in the first apparatus (Mizuno, Furutachi, Ishino, & Takasaki, 2010).

The rotation of the body is realized by superimposing two-phase AC signals on the control signals for the *x*- and. *y*-directions. The rotation about the vertical axis (*z*-axis) was achieved. The relation between the excitation frequency and the rotational speed was studied experimentally. The results are summarized in Figure 5. The body is driven up to 3000rpm. Since the principle of rotation is same as that of induction motor, the slip is observed in higher frequency regions.

The rotation around a horizon axis was expected to be achieved similarly. However, due to the non-uniformity of the magnetic fields, such rotation was prevented by drag torque caused by eddy currents induced in the surface of the ball. To achieve rotation around an arbitrary axis, therefore, surface rotating ball is proposed in this work.

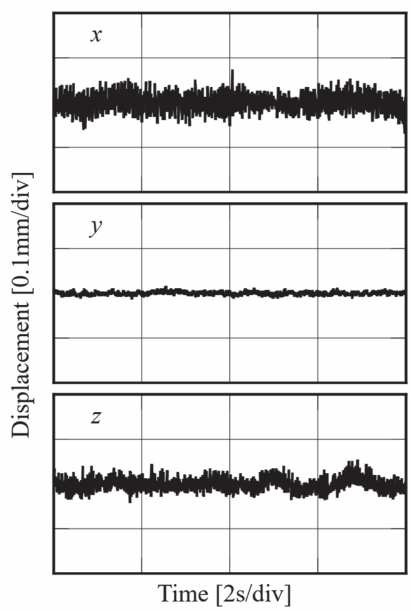


Figure 4: Steady-state displacements of the object in a wind of 6 m/s.

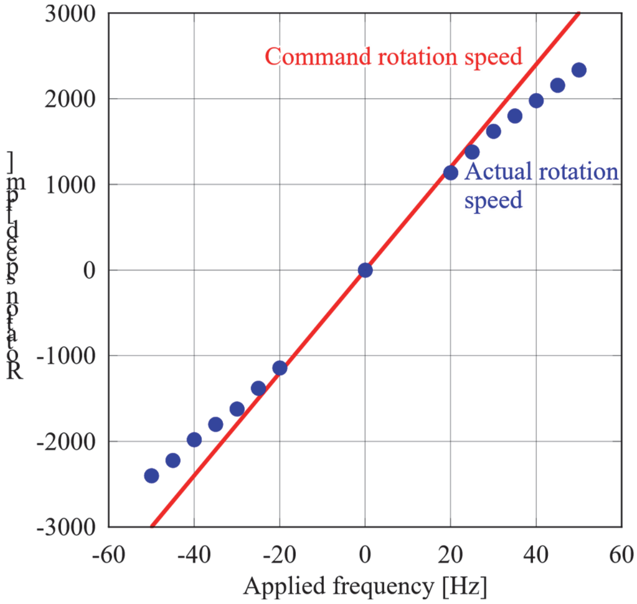
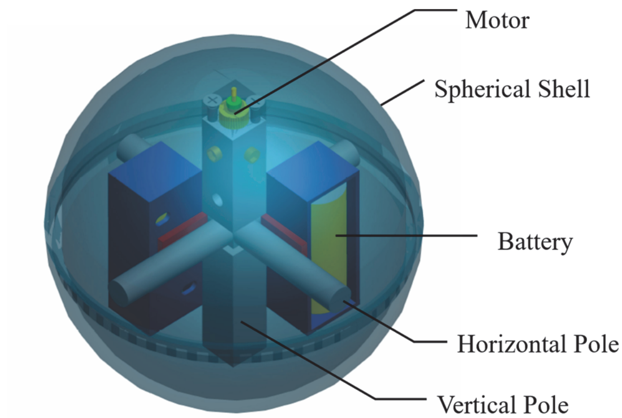


Figure 5: Relation between the rotational speed and the frequency of two-phase AC signal.



3 Surface Rotating Ball

3.1 Basic concept

A schematic view of surface-rotating ball is shown by Figure 6. It has a ferromagnetic structure for magnetic suspension inside and a rotating nonconductive spherical shell enfolding the structure. A motor is fixed at the center frame of the structure to rotate the sphere shell. In wind-tunnel testing, the enfolding spherical shell rotates while the enfolded structure maintains its position and attitude. Thereby, no eddy-current is induced even though the spherical shell is rotating so that no drag torque due to eddy-current is produced.

3.2 Fabricated ball

Figure 7 shows a picture of the fabricated ball. The inside structure has six magnetic poles which face the poles of the magnetic suspension system shown by Figure 8. They are made of SS400. The vertical (central) magnetic core with two poles is a rectangular column with square bases of 9×9 mm. The horizontal magnetic core is a cylinder with circular bases of $\phi 6$ mm.

The outside shell is a sphere with a diameter of 75 mm, which corresponds to the size of a baseball. It is made of nonmagnetic and nonconductive material (nylon). A motor for rotating shell, its driver circuit and a battery are included in the ball. The spherical shell consists of two semi-spheres that can be divided in installing the enfolded components and then assembled.

4 Realization of Rotation during Levitation

The magnetic suspension mechanism shown by Figure 2 is used to suspend the fabricated ball. Because the distance between the poles facing each other is 90 mm, it is too small to conduct wind-

Figure 7: Picture of fabricated ball

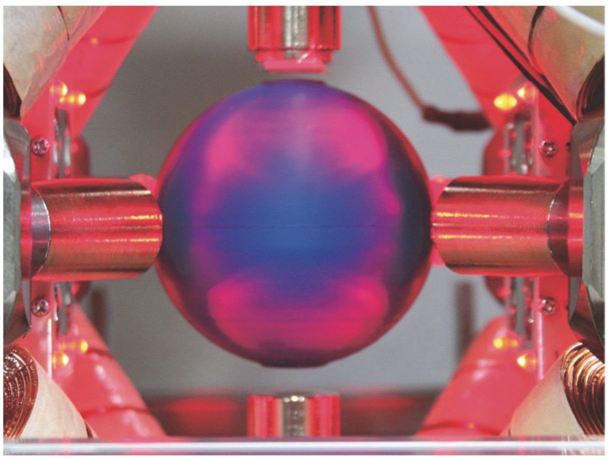


Figure 8: Picture of suspended ball

tunnel tests. In this work, however, suspension tests are carried out to examine the operation of the fabricated ball.

Stable suspension is achieved by applying PID control. Figure 8 shows a picture of the ball during levitation. Figure 5 shows the displacements of the ball. It is observed that the position of the ball is kept stably.

Then the rotation of the spherical shell was started. Figure 10 shows the displacement of the ball. The rotational speed is approximately 20 rpm that is expected from the period of the whirling motion of the ball. When the rational speed was increased, the suspension failed because the whirling motion

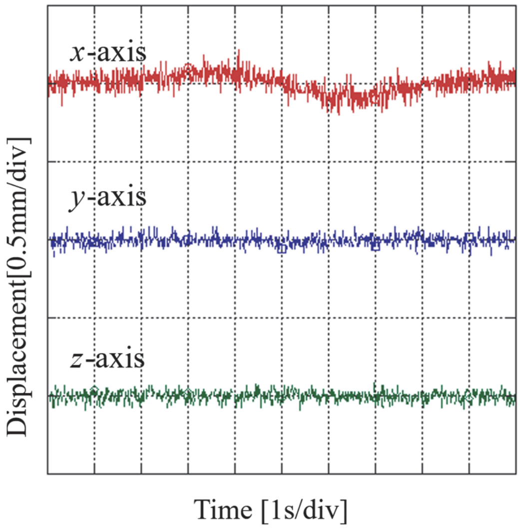


Figure 9: Displacement of ball during levitation

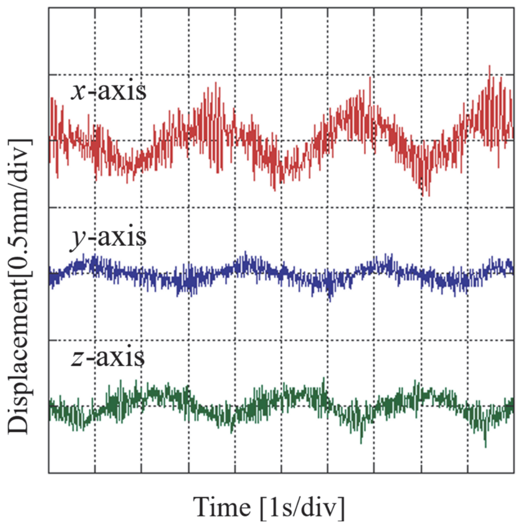


Figure 10: Displacement of ball during rotation

became too large. It is due to the unbalance of the rotating part. It can be improved by mechanically balancing or by introducing unbalance compensation (Mizuno, Analysis on the Fundamental Properties of Active Magnetic Bearing Control Systems by a Transfer Function Approach, 2011).

5 Conclusions

A surface-rotating ball was proposed, designed and fabricated. In this ball, the surface spherical shell rotates while the enfolded structure including magnetic cores, a motor, its driver circuit and a battery does not rotate. Therefore, no drag torque due to induced eddy currents is generated. It was experimentally demonstrated that the ball was suspended stably with surface rotation.

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