The 15th International Symposium on Magnetic Bearings, August 3-6, 2016, Mojiko Hotel, Kitakyushu, Japan

ISMB15

Design of an enlarged wind tunnel system for spinning body using magnetic suspension

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Abstract

A new wind tunnel system for a spinning body is designed for the measurement of the hydrodynamic forces acting on the body. In this system a ferromagnetic sphere (floator) is considered to be suspended and rotated by electromagnets. The diameter and weight of this floator are 19.5mm and 28.4 g, respectively. For observing the accurate hydrodynamic phenomena around the floator by reducing the interferences with the walls, the cross section of the test chamber of the wind tunnel in the vertical plane is set to be 100×100 mm. Wind flow is considered to be in the negative *x*-axis direction. For compensating the effect of the wind flow, force in the opposite direction is necessary. To make a significant difference of the resultant horizontal force in this direction, the poles are arranged asymmetrically, which is a special characteristic of this design. Stable suspension and three-dimensional positioning of the body is achieved in the developed system. Spinning of the body is realized by superimposing two-phase AC signals on the control signal.

Keywords: Electromagnetic Analysis, Magnetic Suspension, Wind Tunnel, Spinning Body, Hydrodynamic Force, Asymmetric Structure.

1. Introduction

Magnetic suspension provides an ideal way of supporting a model for wind tunnel tests because there is no support interface problem arising with mechanical model support (Boyden, et al., 1985; Sawada, et al., 1994). There are numerous examples of development of magnetic suspension devices for the application in wind tunnels (Shameli, et al., 2007; Lin, et al., 1995; Smith, et al., 1996).

A wind tunnel system for spinning body to measure hydrodynamic forces acting on the body has been fabricated (Mizuno, et al., 2010; Mizuno, et al., 2012). In this system, the body is suspended and rotated by electromagnets. The experimental apparatus has eight electromagnets which are placed around a 60mm × 60mm wind tunnel (Mizuno, et al., 2012). Stable levitation has been achieved by applying PID control. Rotation of the body has been realized by superimposing two-phase AC signals on the control signals for the horizontal directions. The variation of the force with the increase of current through electromagnet is also estimated analytically by using 3D FEM (Hasan, et al., 2015). To understand the capability of the floator to be levitated in the suspended condition during the airflow, analysis was carried out. However this existing arrangement is not still appropriate to observe accurate hydrodynamic phenomena around the floating object and it is required to enlarge the size to reduce the interferences with the walls.

In this work, a new wind tunnel system of 100×100mm is designed and fabricated. The floator is made of ferromagnetic material. It is suspended and rotated by the electromagnets arranged outside the tunnel. In designing the system, wide-gap suspension and position sensing are major considerations because both the electromagnets and sensing devices are set outside of the tunnel. In this system the gap in vertical plane where floator is placed is 120 mm. Three dimensional position sensing and control of the floator is done. Wind flow is considered from the negative *x*- axis direction. For compensating this force, the poles and electromagnets are placed asymmetrically. Before designing the system electromagnetic analyses are carried out with an analysis software. Several experiments are carried out for the comparison with the analytical results.

2. New Apparatus

Figure 1 shows photo of the fabricated apparatus from the negative *x*- axis direction. The magnetic suspension system, electromagnets, poles, sensors are in-between two circular plates, the top and the bottom. The diameter and thickness of both of the plates are 420 mm and 30mm, respectively. Among these, the top plate is of magnetic material, soft iron to support the path for the magnetic flux flow. To avoid the saturation of the magnetic flux, the plate is designed sufficiently thick. The bottom plate facilitates to hold whole magnetic suspension system as well as the sensors and some other parts used in the system. It is of Aluminum and also thick enough so that magnetic flux does not pass through it. For the flow of magnetic flux there are five poles in this system, one of which is attached with the upper plate. This pole is fixed with the top plate not in exact center rather 20 mm apart from the center in the positive *x*- axis direction. Other four, each of which is placed on one side of a rectangular shaped block of soft iron which is fixed with the bottom plate. The other side of the block contains the pole holding the electromagnets. Eight sub-coils are connected in series and termed as coil in the later portion. Among the four rectangular cores, two are of small and identical size of 145×80×40 mm and other two are of 167.5×80×40 mm. The cores are fixed with the bottom plate in 45-degree angle with the horizontal centerline. As the upper pole is fixed with the top plate eccentrically, the center of the orientation of the blocks is also eccentric it means 20 mm apart from the center of the plate. Due to this reason, the lateral distance between coil 1 and coil 2 is less than that of coil 3 and coil 4.

Figure 2 shows the arrangement of the complete system. Wind flow is considered to be in the negative *x*-axis direction. For compensating the effect of the wind flow, force in the opposite direction is necessary. To make a significant

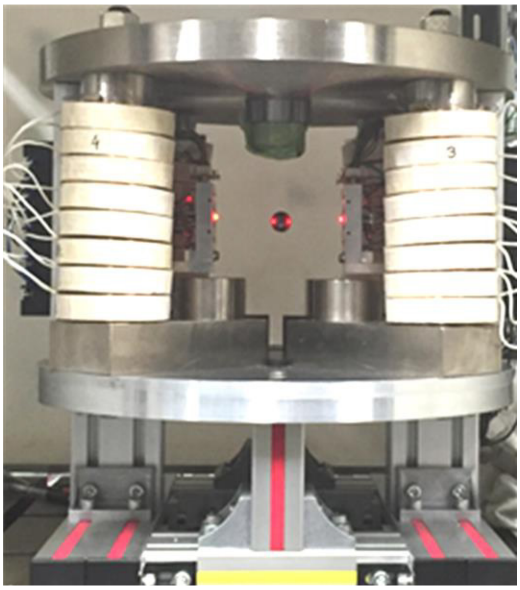


Fig.1 Photo of the fabricated apparatus during levitation

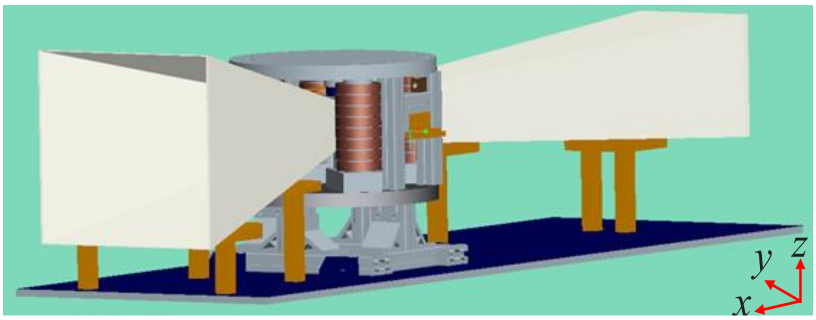


Fig. 2 Schematic diagram of the complete arrangement

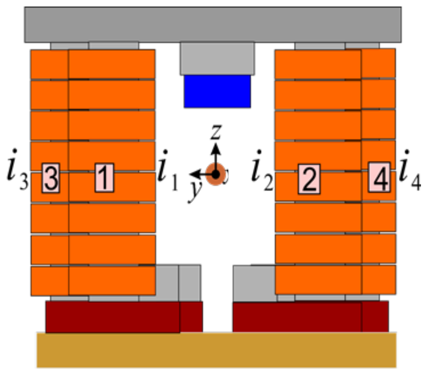


Fig. 3 Magnetic suspension system of the fabricated apparatus

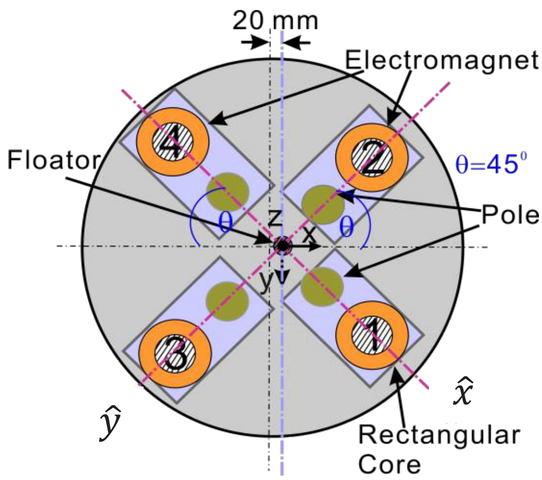


Fig. 4 Schematic diagram showing different components of the system. Floator is placed 20mm apart from the center position; poles and rectangular cores are oriented with an angle of 45^0 with the horizontal centerline. Axis $\hat{x}-\hat{y}$ is considered to be 45^0 clockwise direction of axis *x-y*.

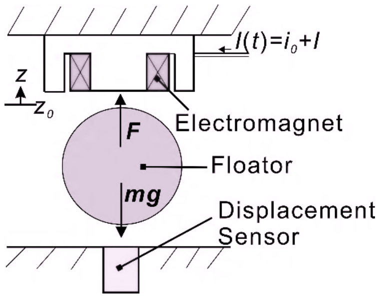


Fig. 5 Basic single degree of freedom magnetic suspension system

difference of the resultant horizontal force in that direction, the poles are arranged asymmetrically and also the upper pole is fixed with the top plate eccentrically as mentioned above, which is a special characteristic of this design. A permanent magnet of material NdFeB, dimension of which is ϕ50× 20 mm is attached to the head of magnetic pole in the vertical direction for compensating the gravitational force acting on the body. The vertical distance between the permanent magnet and the lower pole, where the floator is levitated and wind tunnel will be placed is 120mm. A schematic drawing of the magnetic suspension system of the arrangement is shown in Fig.3. The arrangement of the electromagnets and poles are shown in Fig.4. From the output of the DSP based digital controller through power amplifier, the required coil current is supplied to the system. In this model only four power amplifier is used to supply current to the four coils rather than the previous system (Mizuno, et al., 2012), where eight power amplifiers were used.

3. Modelling

The basic configuration of the magnetic suspension system is shown in Fig. 5. The model consists of an electromagnet which is used to generate magnetic force in upward direction for the controlling of the floating object (floator) of mass m. The motion of the suspended object is assumed to be only in the vertical translational direction. Considering steady state condition and linearization, the equation of motion of the system is given by:

$$m\ddot{z} - K_i i - K_s z = 0 \tag{1}$$

The above is the fundamental equation of a magnetically suspended system in single DOF. To get a more detail of the distribution of the forces on the floator, $\hat{x}-z$ cross section of the system is taken initially. The horizontal and vertical forces acting on the floator is calculated. Later on forces acting on the floator at *x-y-z* plane in different directions is calculated.

3.1 Vertical forces acting on the floator

The electromagnet and pole arrangement of the magnetic suspension system of the fabricated system is shown in Fig.3. The arrangement has four coils, each of which contains 8 sub-coils. The sub-coils in the coil generates magnetic force in upward direction for controlling of the floating object (floator) of mass m. The motion of the floator is assumed to be in translational direction. For the simplification of the calculation a new $\hat{x}-\hat{y}-z$ axis is taken in consideration where the orientation of $\hat{x}-\hat{y}$ is 45^0 clockwise of *x-y* axis as shown in Fig. 4.

Figure 6(a) shows the forces acting on the floator while initially $\hat{x}-z$ cross section of the system is considered. The resultant of these forces in $\hat{x}-z$ axis is given in Fig. 6(b). Here $f_{\hat{x}_1}$ and $f_{\hat{x}_4}$ are the forces acting between the floator and pole 1 and 4 respectively and f_z is the $z-$ directional force on the floator , $f^p_{\hat{x}_q}$ $(p=x,z$ and $q=1{,}4)$ are the resultant of these forces in $\hat{x}$ and z directions and θ_q are the vertical angles between the floator and the poles. The forces acting on the floator due to the vertical movement of the floator is shown in Fig. 6(c). The term, $f^{\hat{x}z}_{\hat{x}_q}$ are the resultant of the forces $f^{\hat{x}}_{\hat{x}_q}$ in vertical direction. Here, $f^z_{\hat{x}_1}=f_{\hat{x}_1}cos\theta_1$ and $f^z_{\hat{x}_4}=f_{\hat{x}_4}cos\theta_2$, also $f^{\hat{x}}_{\hat{x}_1}=f_{\hat{x}_1}sin\theta_1$ and $f^{\hat{x}}_{\hat{x}_4}=f_{\hat{x}_4}sin\theta_2$. Considering the vertical motion of the floator the force balance equation can be written as

$$m\ddot{z}=f_z-f^z_{\hat{x}_1}-f^z_{\hat{x}_4}-f^{\hat{x}z}_{\hat{x}_1}-f^{\hat{x}z}_{\hat{x}_4}-mg \tag{2}$$

where

$$f_z=mg+K^z_{i_1}i_1+K^z_{i_4}i_4+K^{zz}_s z, \tag{3}$$

$$f^z_{\hat{x}_1}+f^z_{\hat{x}_4}+f^{\hat{x}z}_{\hat{x}_1}+f^{\hat{x}z}_{\hat{x}_4}=-K^{\hat{x}}_{i_1}i_1-K^{\hat{x}}_{i_4}i_4-K^{\hat{x}z}_s z \tag{4}$$

Here $K^{\hat{p}}_{i_q}$ are the current coefficient of the electromagnets q in $\hat{p}$- directions, $K^{\hat{p}z}_s$ are the gap-force coefficients for $\hat{p}$-directional force in *z*- direction. Substituting Eq. (3) and (4) to Eq. (2) we get:

$$m\ddot{z}=K^z_{i_1}i_1+K^z_{i_4}i_4+K^{\hat{x}}_{i_1}i_1+K^{\hat{x}}_{i_4}i_4+K^{zz}_s z+K^{\hat{x}z}_s z \tag{5}$$

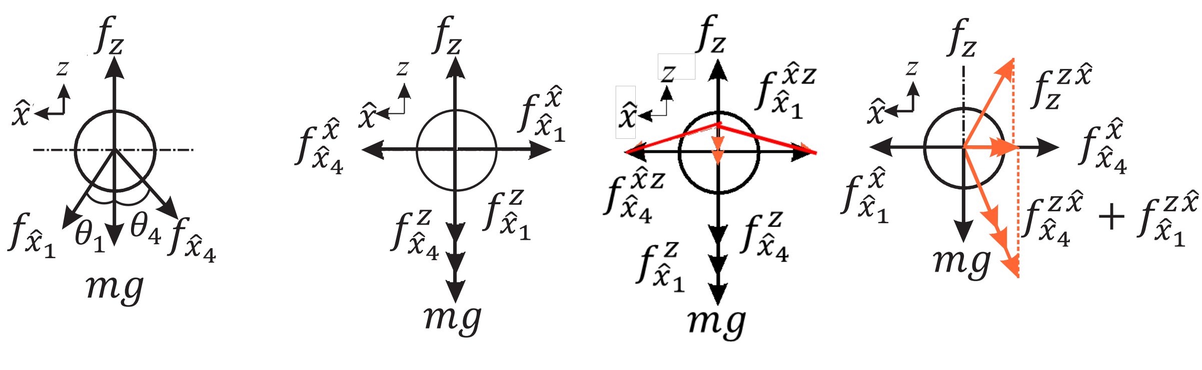
For force in *x-y-z* direction Eq. (5) can be written as:

$$m\ddot{z}=(K^x_{i_1}+K^y_{i_1}+K^z_{i_1})i_1+(K^x_{i_2}+K^y_{i_2}+K^z_{i_2})i_2+(K^x_{i_3}+K^y_{i_3}+K^z_{i_3})i_3+(K^x_{i_4}+K^y_{i_4}+K^z_{i_4})i_4+(K^{xz}_s+K^{yz}_s+K^{zz}_s)z \tag{6}$$

where $K^p_{i_q}=\frac{1}{\sqrt{2}}K^{\hat{p}}_{i_q}$ (*p*= *x, y, z* and *q*=1..4) and $K^{pz}_s=\frac{1}{\sqrt{2}}K^{\hat{p}z}_s$

3.2 Horizontal forces acting on the floator

Figure 6(d) shows the horizontal forces acting on the floator when the forces on the floator is considered to be in the



(a) (b) (c) (d)

Fig. 6(a) Forces acting on the floator when $\hat{x}-z$ cross section is considered, (b) resultant of these forces acting on $\hat{x}-z$ axis direction, (c) vertical forces acting on the floator, (d) horizontal forces acting on the floator positive $\hat{x}-$ axis direction. Here $f_z^{z\hat{x}}$ is the resultant of f_z and $f_{\hat{x}_q}^{z\hat{x}}$ are the resultants of the force $f_{\hat{x}_q}^{z}$ in horizontal direction. The force balance equation can be written as:

$$m\ddot{\hat{x}}=f_{\hat{x}_1}^{\hat{x}}-f_{\hat{x}_4}^{\hat{x}}-f_z^{z\hat{x}}-f_{\hat{x}_4}^{z\hat{x}}-f_{\hat{x}_1}^{z\hat{x}} \tag{7}$$

where

$$f_{\hat{x}_1}^{\hat{x}}-f_{\hat{x}_4}^{\hat{x}}= K_{i_1}^{\hat{x}}i_1-K_{i_4}^{\hat{x}}i_4+K_s^{\hat{x}\hat{x}}\hat{x} \tag{8}$$

$$f_z^{z\hat{x}}+f_{\hat{x}_4}^{z\hat{x}}+f_{\hat{x}_1}^{z\hat{x}}=-K_{i_1}^{z}i_1+K_{i_4}^{z}i_4-K_s^{z\hat{x}}\hat{x}. \tag{9}$$

Here, $K_s^{\hat{p}x}$ are the gap-force coefficients for $\hat{p}$- directional force in $\hat{x}$- direction. Substituting Eq. (8) and (9) to Eq. (7) we get:

$$m\ddot{\hat{x}}=K_{i_1}^{\hat{x}}i_1-K_{i_4}^{\hat{x}}i_4+K_s^{\hat{x}\hat{x}}\hat{x}+K_{i_1}^{z}i_1-K_{i_4}^{z}i_4+K_s^{z\hat{x}}\hat{x}=(K_{i_1}^{\hat{x}}+K_{i_1}^{z})i_1-(K_{i_4}^{\hat{x}}+K_{i_4}^{z})\ i_4+(K_s^{\hat{x}\hat{x}}+K_s^{z\hat{x}})\hat{x} \tag{10}$$

For the complete system, the force equation in $\hat{x}$ direction:

$$m\ddot{\hat{x}}=(K_{i_1}^{\hat{x}}+K_{i_1}^{\hat{y}}+K_{i_1}^{z})i_1+(K_{i_2}^{\hat{x}}+K_{i_2}^{\hat{y}}+K_{i_2}^{z})i_2-(K_{i_3}^{\hat{x}}+K_{i_3}^{\hat{y}}+K_{i_3}^{z})i_3-(K_{i_4}^{\hat{x}}+K_{i_4}^{\hat{y}}+K_{i_4}^{z})i_4+(K_s^{\hat{x}\hat{x}}+K_s^{\hat{y}\hat{x}}+K_s^{z\hat{x}})\ \hat{x} \tag{11}$$

For force in *x-y-z* direction Eq. (11) can be written as:

$$m\ddot{x}=(K_{i_1}^{x}+K_{i_1}^{y}+K_{i_1}^{z})i_1+(K_{i_2}^{x}+K_{i_2}^{y}+K_{i_2}^{z})i_2-(K_{i_3}^{x}+K_{i_3}^{y}+K_{i_3}^{z})i_3-(K_{i_4}^{x}+K_{i_4}^{y}+K_{i_4}^{z})i_4+(K_s^{xx}+K_s^{yx}+K_s^{zx})x, \tag{12}$$

where $K_{i_q}^{p}=\frac{1}{\sqrt{2}}K_{i_q}^{\hat{x}}$ and $K_s^{px}=\frac{1}{\sqrt{2}}K_s^{\hat{p}\hat{x}}(p=x,y,z \text{ and } q=1..4\ )$.

So the equations of motion of the system are:

$$m\ddot{x}=(K_s^{xx}+K_s^{yx}+K_s^{zx})x+(K_{i_1}^{x}+K_{i_1}^{y}+K_{i_1}^{z})i_1+(K_{i_2}^{x}+K_{i_2}^{y}+K_{i_2}^{z})i_2-(K_{i_3}^{x}+K_{i_3}^{y}+K_{i_3}^{z})i_3-(K_{i_4}^{x}+K_{i_4}^{y}+K_{i_4}^{z})i_4$$

$$m\ddot{y}=(K_s^{xy}+K_s^{yy}+K_s^{zy})y+(K_{i_1}^{x}+K_{i_1}^{y}+K_{i_1}^{z})i_1-(K_{i_2}^{x}+K_{i_2}^{y}+K_{i_2}^{z})i_2+(K_{i_3}^{x}+K_{i_3}^{y}+K_{i_3}^{z})i_3-(K_{i_4}^{x}+K_{i_4}^{y}+K_{i_4}^{z})i_4$$

$$m\ddot{z}=(K_s^{xz}+K_s^{yz}+K_s^{zz})z+(K_{i_1}^{x}+K_{i_1}^{y}+K_{i_1}^{z})i_1+(K_{i_2}^{x}+K_{i_2}^{y}+K_{i_2}^{z})i_2+(K_{i_3}^{x}+K_{i_3}^{y}+K_{i_3}^{z})i_3+(K_{i_4}^{x}+K_{i_4}^{y}+K_{i_4}^{z})i_4$$

In the above derived equations, the displacement of the floator is assumed to be in *x*-, *y*- and *z*- directions only, when force is considered in these directions. But due to the applied force in one direction if there is interaction in other directions, it is necessary to consider the effect of the orthogonal forces in those directions as well. With this consideration the general form of the equation of motion of the system in 3DOF can be given by the following relationship:

$$m\begin{bmatrix}\ddot{x}\\ \ddot{y}\\ \ddot{z}\end{bmatrix}=\begin{bmatrix}k_s^{xx} & k_s^{xy} & k_s^{xz}\\ k_s^{yx} & k_s^{yy} & k_s^{yz}\\ k_s^{zx} & k_s^{zy} & k_s^{zz}\end{bmatrix}\begin{bmatrix}x\\ y\\ z\end{bmatrix}+\begin{bmatrix}k_{i_1}^{x} & k_{i_2}^{x} & k_{i_3}^{x} & k_{i_4}^{x}\\ k_{i_1}^{y} & k_{i_2}^{y} & k_{i_3}^{y} & k_{i_4}^{y}\\ k_{i_1}^{z} & k_{i_2}^{z} & k_{i_3}^{z} & k_{i_4}^{z}\end{bmatrix}\begin{bmatrix}i_1\\ i_2\\ i_3\\ i_4\end{bmatrix} \tag{13}$$

4. Control system

The operation of the electromagnets to control the motions of the floator is explained in the following. To control the vertical motion, current is supplied in all electromagnets which means that current passes through every coil in upward direction which generates a magnetic flux flow through the upper pole to the lower poles. As the current increases, the flux density as well as magnetic force in upward direction also increases. From Eq. (13) the control force $\boldsymbol{f}$ is written as:

$$\boldsymbol{f}=\mathbf{K}_{\boldsymbol{i}}\boldsymbol{i} \tag{14}$$

The relationship between coil current i_j and the current acting in *x*-, *y*- and *z*- directions i_x, i_y and i_z can be given by:

$$\boldsymbol{i} = \mathbf{C}\boldsymbol{i_c} = \begin{bmatrix} c_{1x} & c_{1y} & c_{1z} \\ c_{2x} & -c_{2y} & c_{2z} \\ -c_{3x} & c_{3y} & c_{3z} \\ -c_{4x} & -c_{4y} & c_{4z} \end{bmatrix} \begin{bmatrix} i_x \\ i_y \\ i_z \end{bmatrix} \tag{15}$$

where $c_{ix......z}(i = 1..3)$ are the current constants. Due to the symmetry of the orientation of the poles, $c_{1x} = c_{2x}$, $c_{1y} = c_{2y}$, $c_{1z} = c_{2z}$ and $c_{3x} = c_{4x}$, $c_{3y} = c_{4y}$, $c_{3z} = c_{4z}$ and assuming $k^x_{i_1} = k^x_{i_2}$, $k^y_{i_1} = k^y_{i_2}$, $k^z_{i_1} = k^z_{i_2}$ and $k^x_{i_3} = k^x_{i_4}$, $k^y_{i_3} = k^y_{i_4}$, $k^z_{i_3} = k^z_{i_4}$ and by substituting these values in Eq. 15, the control force can be obtained as:

$$\boldsymbol{f} = \mathbf{K}_{\boldsymbol{i}}\mathbf{C}\boldsymbol{i_c} = \begin{bmatrix} k^x_{i_1} & k^x_{i_1} & -k^x_{i_3} & -k^x_{i_3} \\ k^y_{i_1} & -k^y_{i_1} & k^y_{i_3} & -k^y_{i_3} \\ k^z_{i_1} & k^z_{i_1} & k^z_{i_3} & k^z_{i_3} \end{bmatrix} \begin{bmatrix} c_{1x} & c_{1y} & c_{1z} \\ c_{1x} & -c_{1y} & c_{1z} \\ -c_{3x} & c_{3y} & c_{3z} \\ -c_{3x} & -c_{3y} & c_{3z} \end{bmatrix} \begin{bmatrix} i_x \\ i_y \\ i_z \end{bmatrix}$$

$$= \begin{bmatrix} 2\left(k^x_{i_1}c_{1x} + k^x_{i_3}c_{3x}\right) & 0 & 2\left(k^x_{i_1}c_{1z} - k^x_{i_3}c_{3z}\right) \\ 0 & 2\left(k^y_{i_2}c_{1y} + k^y_{i_3}c_{3y}\right) & 0 \\ 2\left(k^z_{i_1}c_{1x} - k^z_{i_3}c_{3x}\right) & 0 & 2\left(k^z_{i_1}c_{1z} + k^z_{i_3}c_{3z}\right) \end{bmatrix} \begin{bmatrix} i_x \\ i_y \\ i_z \end{bmatrix}$$

For system without any interaction, the $\mathbf{K}_{\boldsymbol{i}}\mathbf{C}$ matrix should be diagonal which implies, the following conditions should be satisfied:

$$k^x_{i_1}c_{1z} - k^x_{i_3}c_{3z} = 0 \tag{16}$$

and

$$k^z_{i_1}c_{1x} - k^z_{i_3}c_{3x} = 0. \tag{17}$$

From Eq. (16) and Eq. (17), the following relationships are obtained:

$$\frac{c_{1x}}{c_{3x}} = \frac{k^z_{i_3}}{k^z_{i_1}} \text{ and } \frac{c_{1z}}{c_{3z}} = \frac{k^x_{i_3}}{k^x_{i_1}}. \tag{18}$$

From Eq. (15), the coil current are represented as:

$$\boldsymbol{i} = \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -1 & 1 \\ -\alpha & 1 & \beta \\ -\alpha & -1 & \beta \end{bmatrix} \begin{bmatrix} i_x \\ i_y \\ i_z \end{bmatrix} \tag{19}$$

where $\alpha = \frac{k^z_{i_1}}{k^z_{i_3}}$ and $\beta = \frac{k^x_{i_1}}{k^x_{i_3}}$. The values of α and β are obtained from the analytical results of k_i.

The values are then placed in controller for the system control without interaction during wind flow in *x*- direction. To control the lateral motion, the four electromagnets in the same plane are operated differentially. For example, to increase the force in the *x*-direction, the currents of the coils 1 and 2 are increased and those of the coils 3 and 4 are decreased with a factor α. With similar action in *z*- direction the currents in coils 3 and 4 are increased with a factor β and in *y*- direction current increases in coil 1 and 3 while decreases in coil 2 and 4 proportionately. The outputs of the sensors are inputted into a DSP-based digital controller. The controller calculates control signals and send them together to power amplifier for the electromagnets through D/A converters.

5. Experimental Results
5.1 Estimation of Vertical Force

The vertical force acting on the floator is measured with a measurement device (Hasan, et al., 2015). Initially, the constant current required for the levitation of the object is supplied and as the ball is placed approximately at the point of levitation, there is some deflection in the output of the load cell. When the current supply is increased through the coils, the ball experiences some increase in the upward direction attractive force. The more the amount of the current in the coils increases the more the force increases. A calibration is taken out to get a relationship between the actual force and the measured force based on the output of the strain amplifier. Experimentation is carried out by supplying constant current through the electromagnets and force is measured for increasing current in the coils. Figure 7 shows the comparison of the results obtained by 3D analysis and experiment. It is observed that there is similarity in the variation of the force with current for both cases. Initially at zero current for both cases there is some force on the floator because of the effect of permanent magnet on the floator.

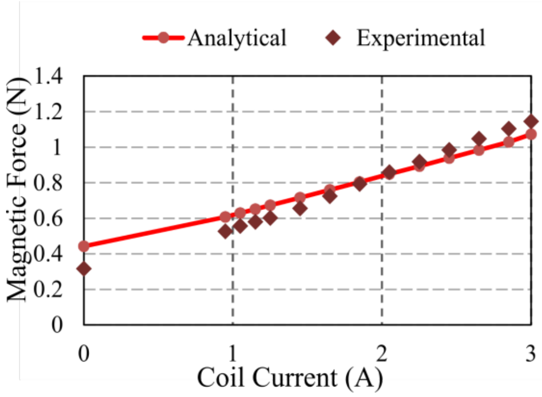


Fig.7 Comparison of magnetic forces with coil current increase

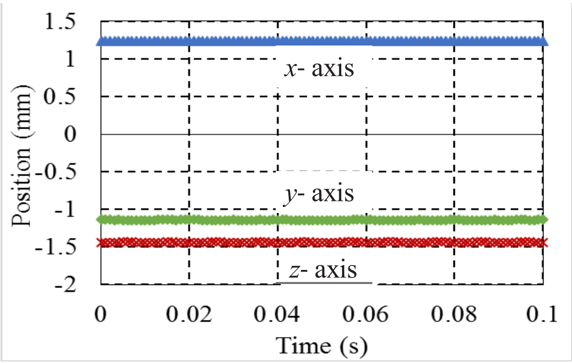


Fig. 8 Position of the floator during PD control

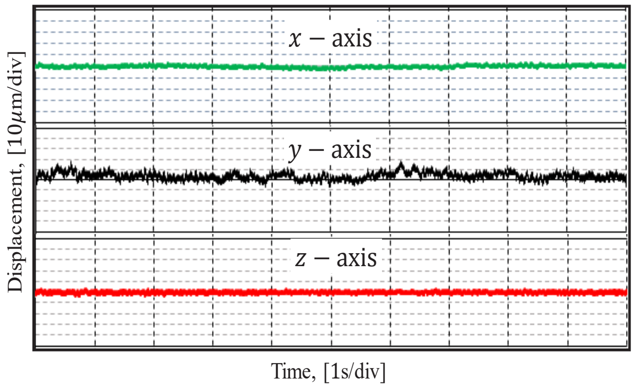


Fig. 9 Displacement of the floator with respect to the reference position during levitation with IP-D control

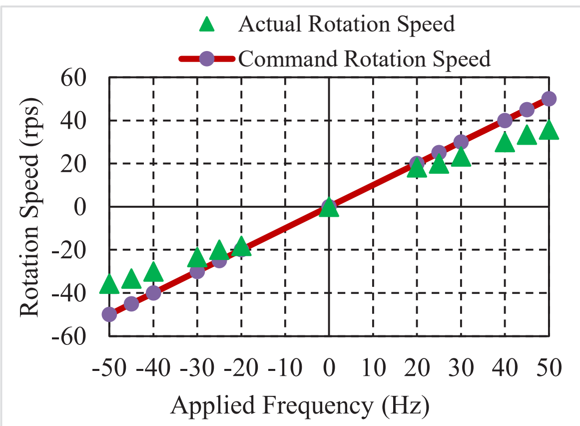


Fig.10 Relation between Applied frequency and rotation speed

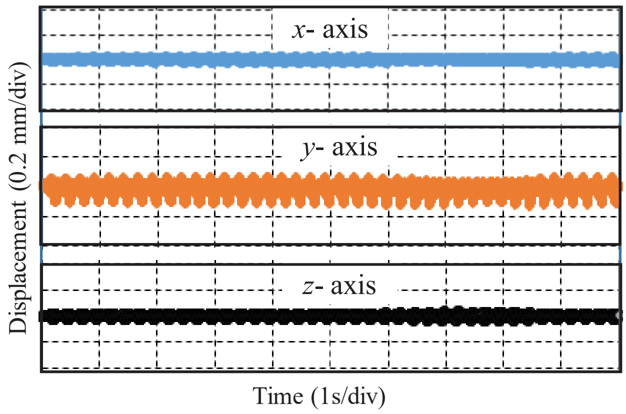


Fig. 11 Displacement of the floator during rotation

5.2 Levitation and Rotation

The levitation of the ball is first achieved by applying PD control. The levitation position of the ball is shown in Fig. 8. This position is taken to be as reference position. For *x*- axis direction, the reference position is +1.3 mm while for y- and z- axis it is -1.05mm and -1.45mm respectively. To keep the object in that position this value is subtracted from the sensor signal value before applying the integral and proportional control. Figure 9 shows the displacement of the floator during levitation with respect to the reference position during IP-D control. Average current required for levitation is 0.45A for coil 1 and coil 2. For coil 3 and coil 4 it is 0.63A. 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) is achieved. Figure 10 shows the relation between the excitation frequency and rotational speed, which is studied experimentally. The amplitude is kept constant while the frequency of the applied sine wave is increased. As frequency increased, the rotational speed of the floator also increased. The body is driven up to 3000 rpm in both clockwise and anti-clockwise directions. The slip is observed at higher frequency regions. Figure 11 shows the displacement pattern of the floator during rotation while IP-D control is applied in the system.

6. Conclusion

A wind-tunnel system with 100 ×100 mm was designed and fabricated. Modelling of the system was done considering the forces acting on the floator in horizontal and vertical directions. Electromagnetic analyses were carried out and the magnetic force acting on the floator was estimated. The variation of that force with the increase of current in electromagnets was also obtained. The body was successfully levitated and rotated. It was observed that slip occurs at higher frequency regions.

Further Work

The hydrodynamic forces acting on the spinning body is to be measured. As IP-D control is applied in this experiment, the fluid drag and lift force can be measured from the control input directly. By varying the wind speed, variation of these forces will also be observed.

Acknowledgement

This work was supported by JSPS KAKENHI Grant Number 25289048.

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