MAGNET WHEEL USING PERMANENT MAGNETS FOR REPULSIVE MAGNETIC LEVITATION AND INDUCTION TYPE THRUST

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SUMMARY

A revolving permanent magnet type magnetic wheel called the "magnet wheel" is shown, which has both functions of inductive repulsive-type magnetic levitation and thrust. The characteristics of two types of the "tilt type magnet wheel" and the "partial overlap magnet wheel" are studied respectively by using a test facility and three-dimensional numerical analysis. The lift force, the thrust and the lateral force characteristics at standstill are shown versus revolving speed, the mechanical clearance, the conductivity of conducting plate, the arrangement of magnets, the volume of magnets, the tilt angle for the tilt type and the overlap factor for the partial overlap type.

INTRODUCTION

There are many magnetic levitation or propulsion techniques. The author has proposed the "magnet wheel" which is a kind of electromagnetic device with magnetic levitation and propulsion. The magnet wheel produces a rotating magnetic field by mechanically rotating permanent magnets with high coercivity. The induction repulsive-type magnetic lift force is produced by the rotating flux linking to a conducting plate. Simultaneously with the lift force is produced the thrust from the usually detrimental drag torque accompanying copper loss. The author has proposed two variations called "tilt type magnet wheel" and "partial overlap type magnet wheel" respectively [1][2].

Different from these types, a rotating motor type magnetic wheel has been also considered [3]. That is, a synchronous motor is constructed by the outer field-pole of permanent magnets which rotates against the centrally fixed armature winding. With no magnetic shielding, part of the magnetic flux on the outer pole is made to link with a normally placed conducting plate.

The proposed magnet wheel has a large weak point of mechanical rotation, but has the following strong points in induction repulsive type magnetic levitation, which has a self-stability without a complicated controller.

a. This method can produce larger lift force than the weight of mover installed levitation and propulsion device.
b. The useful thrust can be produced from the power required to produce the lift force.
c. The mechanical revolving method enables the operation free of poor power factor typical of ac electromagnets.

A small vehicle model with four magnet wheels of the "partial overlap type" has succeeded in propulsion, levitation and guidance without any control [4].

In this paper, the characteristics of the magnet wheel at standstill are shown, which were obtained by experimental study using a test facility [1] and theoretical study using three-dimensional numerical analysis [5].

WORKING PRINCIPLE OF THE MAGNET WHEEL

The magnet wheel is composed of a rotor with permanent magnets and a conducting plate. Figure 1 and Figure 2 are simplified diagrams of the magnet wheel. The pole faces of the permanent magnets are placed opposite to the conducting plate and are separated by an air gap. When the magnets rotate, the magnetic field which links the conducting plate changes with time producing eddy currents due to induced electromotive force (emf) in the conducting plate. The magnetomotive force (mmf) due to the eddy current faces the magnetic poles of the permanent magnets. The mmf cancels the magnetic flux which traverses from the magnets to the conducting plate, allowing a repulsive levitation force between the magnet wheel and the conducting plate to be produced. In general, a drag torque along the rotation direction will be produced, too. Due to this torque, corresponding amounts of power loss cannot be avoided. To make effective use of the torque, two types of magnet wheels are proposed.

Figure 1 shows the "tilt type magnet wheel", where the permanent magnet rotator (henceforth referred to as "magnet wheel" unless otherwise stated) is inclined to the conducting plate such that there is a varying air gap. Figure 2 shows the "partial overlap type magnet wheel", where the magnet wheel is made to rotate near the edge of conducting plate, so that the rotation region of the magnet wheel partially superimposes the conducting plate. Both types attempt to produce an uneven air gap magnetic flux density distribution in the rotating direction. This uneven distribution will produce a linear force, that is the thrust.

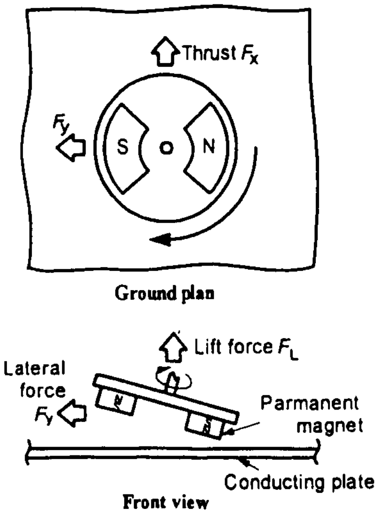


Fig. 1 The "tilt type magnet wheel".

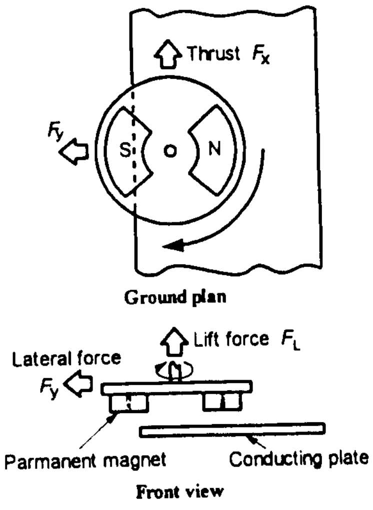
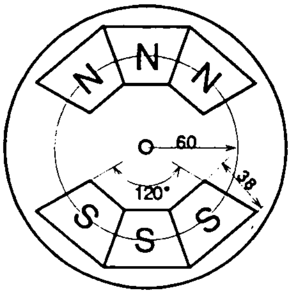


Fig.2 The "partial overlap type magnet wheel".

DATA FOR TESTED WHEEL

Figure 3 shows the form and the dimensions of the tested magnet wheel. 40mm thick neodymium permanent magnets with coercivity of 926kA/m (11,640Oe) and maximum energy product of 345kAT/m (43.3MGOe) are arranged in two poles on a circle of 60mm radius on the disk shaped ferro-magnetic yoke. The magnetization of the permanent magnets is in the direction of the thickness. The surface of the magnet poles is covered by thin non-magnetic stainless steel. This magnet wheel is denoted by the name of MW-A. The following experimental results were obtained by using the test facility installed with this magnet wheel [1].



Specification of permanent magnet	
Type	Neodymium type
Maximum energy product	$(BH)_{\max}$ =345kAT/m
Coercivity	iH_c = 926kA/m
Thickness	h_M = 40mm

Fig. 3 Dimension and arrangement of permanent magnets of the tested magnet wheel (MW-A).

CHARACTERISTICS

Characteristics of Magnetic Levitation Device of Induction Type

Characteristics at the state of parallel rotation are fundamental, in which the magnet wheel is placed in a parallel condition opposite the conducting plate in the tilt type magnet wheel shown in Figure 1. Numerical three-dimensional electromagnetic analysis [1][5] is used to check the characteristics.

Rotating Speed Characteristics

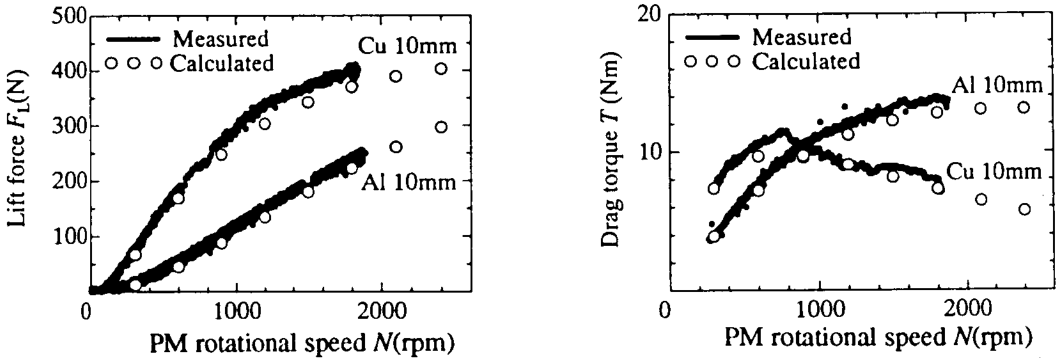
Figure 4(a) shows the lift force versus rotating speed characteristics for 10mm-thick copper plate (Cu) at mechanical clearance of g_2=15mm and 10mm-thick aluminum (alloy) plate (Al) at g_2=10mm respectively. The conductivity of copper and aluminum (alloy) are 5.27×10^7 S/m and 1.79×10^7 S/m respectively. The copper plate with small resistance gives larger lift force that is saturated at a lower rotational speed compared with aluminum. The lift force for the aluminum plate is in proportion to the rotational speed in this range. The rotational speed of 1,800 rpm is equivalent to 11.3 m/s in the tested wheel. Figure 4(b) shows the drag torque versus rotational speed characteristic for the case of Figure 4(a). The maximum torque appears for the copper plate.

Figure 5 shows the comparison between the computed characteristics for copper plate and aluminum plate respectively over a wide speed range. The classical skin effect is not considered in the calculation because the thickness of conductor is divided into only two layers. The saturated value of lift force is fixed independently of the resistance of conductor, and the rotational speed for saturation is proportional to the resistance of conductor, as shown in Figure 5(a). The maximum drag torque is fixed independently of the resistance, and the rotational speed for the maximum torque is in proportion to the resistance. This is the same phenomenon as the proportional shifting of torque for rotor resistance in a rotating type induction motor.

Figure 6 shows the measured lift force per driving power of the magnet wheel with respect to the rotational speed. The value of lift force per driving power is almost constant independent of the rotational speed, and dependent of the resistance of the conducting plate.

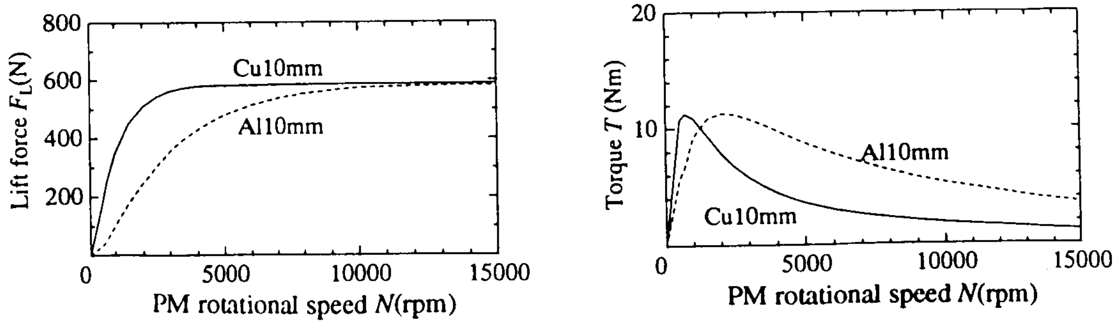
Characteristics for Conductivity of Conducting Plate

Figure 7 shows the relation between the measured lift force per driving power and the surface conductivity, that is the value of conductivity multiplied by the thickness. Cu 10mm means the 10mm-thick conducting plate of copper. The surface conductivity of the 5mm-thick copper plate is almost equal to that of 15mm-thick aluminum (alloy) plate, whose conductivity is 0.34 times as large as that of copper. The lift force per driving power is almost proportional to the surface conductivity.



(a) Lift force (b) Drag torque

Fig. 4 Measured lift force and drag torque characteristics compared with calculated values.



(a) Lift force (b) Drag torque

Fig. 5 Computed lift force and drag torque – rotational speed curves for different secondary conductors.

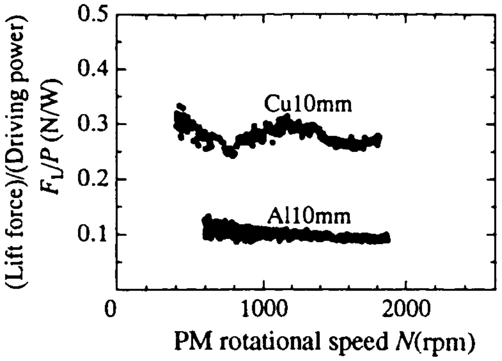


Fig. 6 Lift force per driving power for rotational speed.

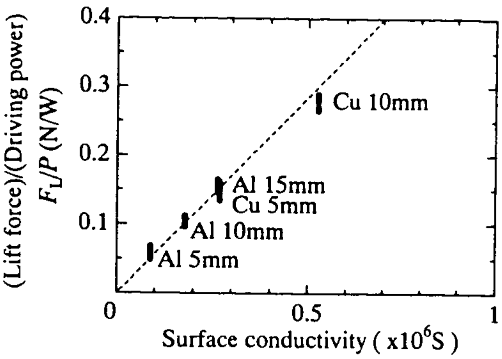


Fig. 7 Lift force per driving power characteristics for surface conductivity.

Influence of Arrangement of Permanent Magnets

Various arrangements of permanent magnets are studied as a parameter for performance of the magnet wheel. Figure 8 shows the five kinds of arrangements of experimental wheels. The MW-B has an arrangement lacking a center magnet of pole of MW-A. The number of poles and the pole pitch are equal to those of MW-A respectively. The total volume of permanent magnets of MW-B is 2/3 as much as the MW-A. The distribution in the direction of the circumference of the magnetomotive force of magnets for MW-B includes a large spatial harmonic component. MW-C is a four-pole arrangement using the magnets of MW-B. The volume of MW-C is equal to that of MW-B. The pole pitch is half of that of MW-A or MW-B. In MW-D and MW-E the thickness of magnets is 20mm, half of that of MW-A. MW-B and MW-C. The number of poles and the pole pitch of MW-D are equal to MW-C. The diameter of MW-E with two-poles is half of the others. The pole pitch of MW-E is equal to that of MW-C or MW-D.

Figure 9 shows the relation between the magnitude of lift force and the total volume of permanent magnets (PMs) for the magnet wheels, using measured values. The rotational speed is fixed at 11.3m/s. The lift force varies as about the 4/3th power of the magnets volume. It seems that the spatial harmonics of flux density of magnets are hardly effective to increase the lift force.

In order to study the influence of the space harmonics of flux distribution, the magnetomotive force of permanent magnets in the direction of circumference is analyzed. The solid line of Figure 10 shows the distribution of magnetomotive force for MW-A. F_m is the amplitude of the magnetomotive force of the magnets. The dotted line represents the fundamental component of the waveform of the solid line. Here the fundamental factor is defined as the ratio between F_m and the root mean square (rms) value expressed by F_1 of the fundamental waveform. That is

$$\text{Fundamental factor: } F_1 / F_m = \frac{\frac{F_{1m}}{\sqrt{2}}}{F_m}$$

Figure 11 shows the relation between the fundamental factor and the lift force per total volume of magnets of one magnet wheel, using measured values. The lift force is approximately proportional to the fundamental factor independently of the resistance of conductor.

Figure 12 shows the relation between the thickness of magnets in the direction of magnetization and the lift force. Here the notations of 2p, 4p and 6p mean 2-pole, 4-pole and 6-pole respectively under the condition that the radius at magnet placement is fixed at 60mm. As the magnet wheel has large magnetic resistance in the magnetic path, the lift force is not saturated even for thick magnets, but the lift force per volume of magnet has an extreme value at some thickness. The value of thickness for the maximum lift force increases as the pole pitch expressed by τ increases.

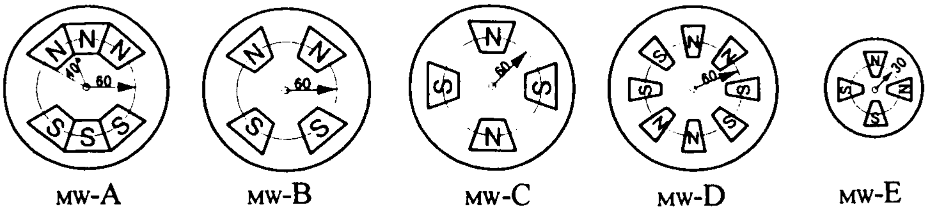


Fig. 8 Name of magnet wheel with different arrangement and size of magnet.

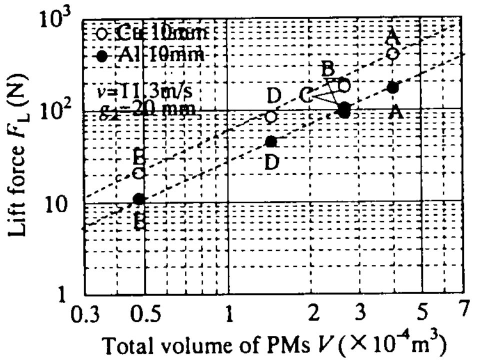


Fig. 9 Relation between magnitude of lift force and total volume of magnets for five magnet wheels.

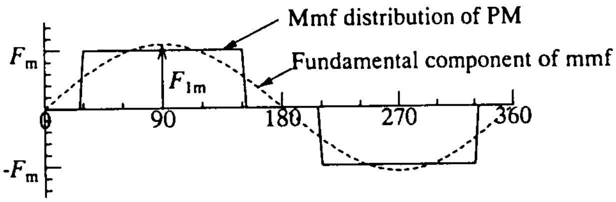


Fig. 10 Magnetomotive force distribution of magnets in the direction of circumference for MW-A.

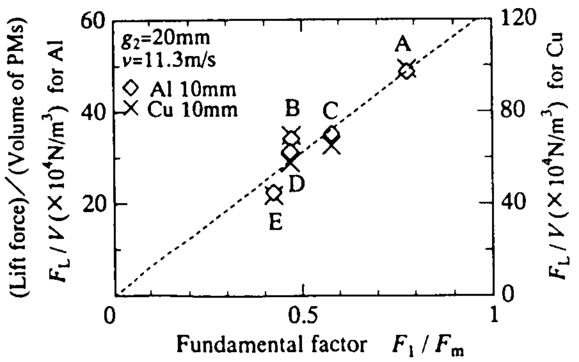


Fig. 11 Lift force per total volume total magnets versus fundamental factor of mmf.

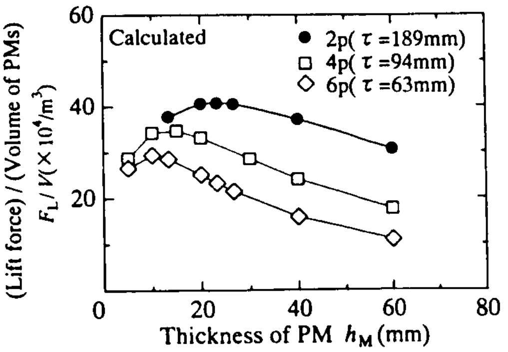


Fig. 12 Lift force per total volume of magnets versus thickness of magnet.

Figure 13 shows the definition of symbols and parameters for the tilt type magnet wheel. The tilt angle is expressed by ϕ. The minimum mechanical clearance between the surface of the magnet wheel and the surface of the conducting plate is expressed by $g_{2,\min}$.

Three Dimensional Force versus Rotational Speed

Figure 14 shows the lift force, the thrust and the lateral force with respect to the rotational speed for the tilt type magnet wheel of MW-A at the condition that the tilt angle is 10 degree, the minimum mechanical clearance is 10mm for 10mm-thick aluminum plate. It can be confirmed that thrust is produced. The lateral force does not appear.

Instantaneous Forces for Revolving Angle Position

Figure 15 shows the instantaneous forces of tilt type magnet wheel which are calculated values. The rotational angle means the mechanical angle that is equal to the electric angle in the case of MW-A with 2-pole. The pulsation appears in the lift force of magnet wheel.

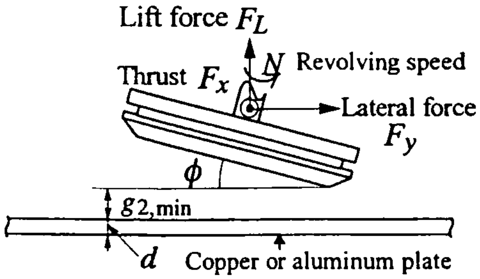


Fig. 13 Definition for the tilt type magnet wheel.

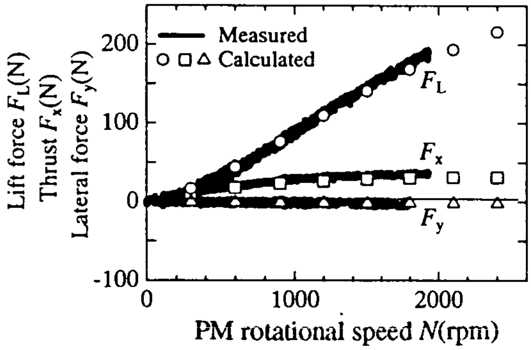


Fig. 14 Force-rotational speed curves for the tilt type magnet wheel at $\phi = 10$ degree.

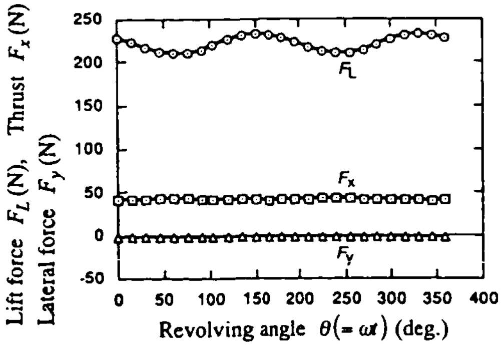
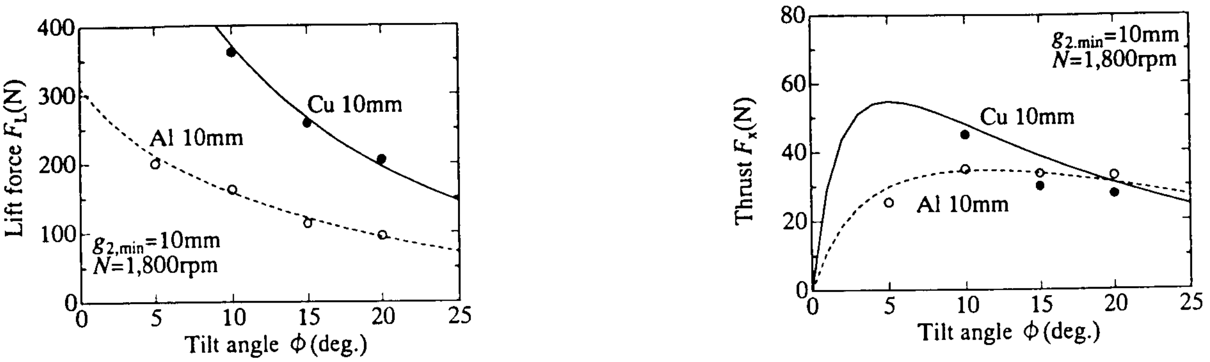


Fig. 15 Fluctuation of forces with rotational angle at the tilt angle of 10 degree and 1,800 rpm.

Characteristics for Tilt Angle and Mechanical Clearance

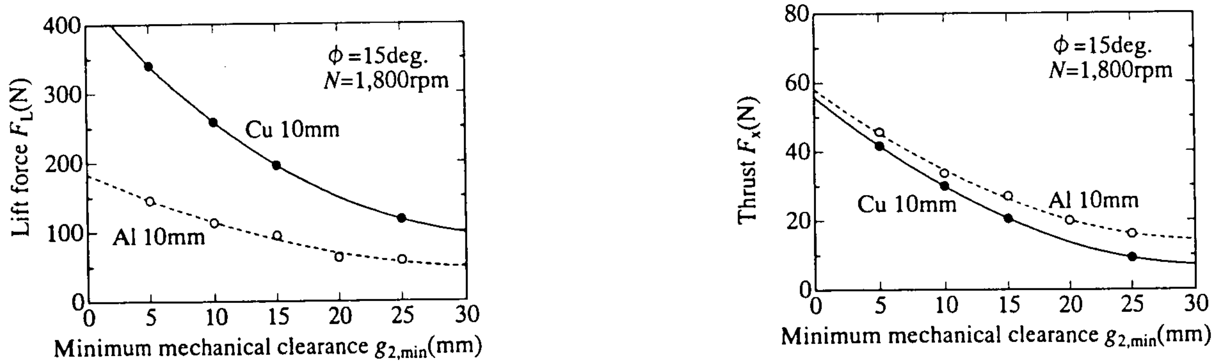
Figure 16(a) and Figure 16(b) show the measured lift force and thrust with respect to the tilt angle respectively for copper and aluminum plates. The minimum mechanical clearance and the rotational speed are fixed at 10mm and 1,800 rpm respectively. The lift force decreases rapidly as the tilt angle increases. The maximum thrust appears at a smaller tilt angle when resistance of conductor is smaller.

Figure 17(a) and Figure 17(b) show the measured lift force and thrust with respect to the mechanical clearance. The tilt angle is fixed at 15 degrees. The large lift force is produced with a small resistance of conductor and small mechanical clearance compared to the size of magnetic wheel. The thrust characteristics do not differ very much with the resistance of conductor.



(a) Lift force (b) Thrust

Fig. 16 Tilt angle characteristics.



(a) Lift force (b) Thrust

Fig. 17 Mechanical clearance characteristics.

Characteristics for Five Arrangements of Magnets

Figure 18 shows the relation between the measured lift force per driving power and the tilt angle for five magnet wheels shown in Figure 8. The lift force per driving power is independent of the tilt angle and the arrangement of magnets.

Figure 19 shows the relation between the tilt angle and the measured transformation for thrust. The transformation is defined as the ratio of the tangential force-induced drag torque to the thrust. The thrust transformation rate increases as the tilt angle increases. The four-pole wheel of MW-C has larger transformation rate compared with two-pole wheel of MW-A.

Figure 20 shows the lift force and the thrust with respect to the total volume of magnets for five tilt type magnet wheels respectively. The tilt angle and the rotational speed are fixed at 10 degree and 11.3m/s respectively. Both lift force and thrust vary as about 4/3th power of the magnets volume as well as the lift force characteristics for the state of parallel rotation shown in Figure 9.

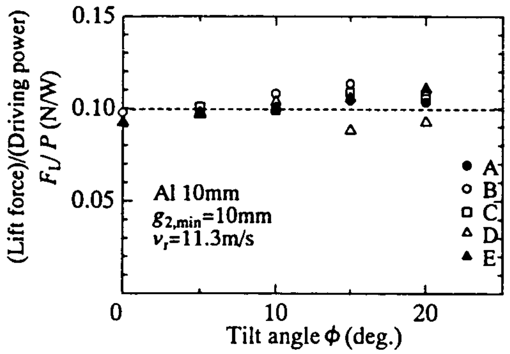


Fig. 18 Lift force per driving power versus tilt angle.

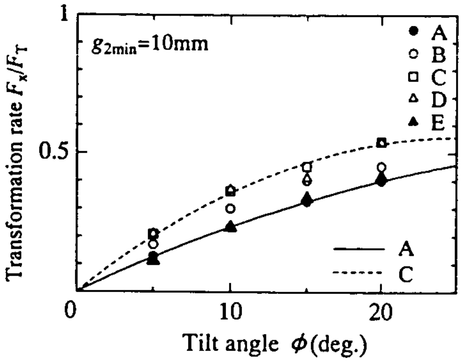


Fig. 19 Transformation rate for thrust versus tilt angle.

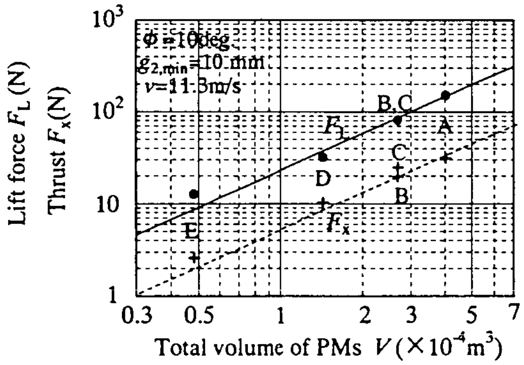


Fig. 20 Measured lift force and thrust for five tilt type magnet wheels.

Characteristics at the "Partial Overlap Type Magnet Wheel"

The directions of forces for the partial overlap type magnet wheel are defined respectively as shown in Figure 21. The overlap area between the magnet wheel and the conducting plate is an important parameter of the partial overlap type magnet wheel. In Figure 21, we let the rotational area of magnetic poles shown by the shadowed portion be S_1, and let the overlap area between S_1 and the conductor region be S_2 shown by the gray portion. Here the overlap factor is defined as $k_y = S_2/S_1$. At the case that the magnet wheel overlaps the conducting plate completely, $k_y = 1.0$.

Three Dimensional Forces versus Revolving Speed

Figure 22 shows the measured lift force, thrust and lateral force with respect to the rotational speed for the overlap type magnet wheel of MW-A for the condition that the overlap factor is 0.66, mechanical clearance is 15mm for 10mm-thick aluminum plate. It can be confirmed that thrust and the lateral force are produced together with lift force. The lateral force acts in the direction away from conducting plate.

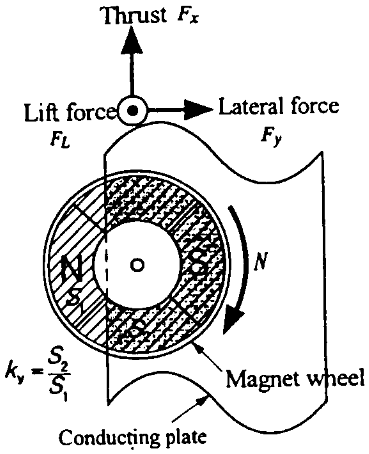


Fig. 21 Definition of direction of forces and the overlap factor k_y.

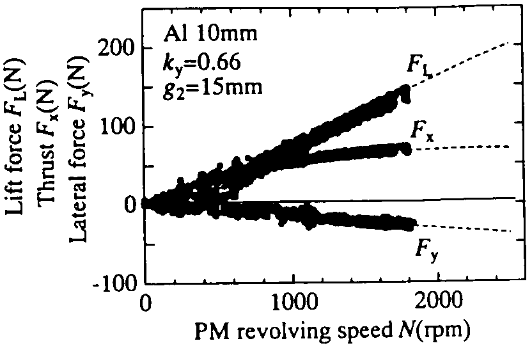


Fig. 22 Measured force-revolving speed curves for the partial overlap type magnet wheel.

Instantaneous Forces for Revolving Angle Position

Figure 23 shows the instantaneous forces of the overlap type magnet wheel with respect to the position of revolving angle at the conditions that the overlap factor is 0.66, mechanical clearance 15mm, rotational speed 1,800rpm for 10mm-thick aluminum plate. The pulsation appears in the lift force and the lateral force. Although the pulsation is relatively large, there will be no problem in the high-speed rotation over 3,000 rpm corresponding to 100 Hz for two-pole wheel.

Characteristics for Overlap Factor and Mechanical Clearance

Figure 24 shows the lift force, the thrust and the lateral force with respect to the overlap factor at the condition that mechanical clearance is 15mm, rotational speed 1,800 rpm for a 10mm-thick aluminum plate. The lift force decreases as the overlap factor decreases. The thrust and the lateral force have extreme values depending on the arrangement of magnets and overlap factor respectively.

Figure 25(a) and Figure 25(b) show the measured lift force and thrust with respect to the mechanical clearance. The overlap factor is fixed at 0.66 which gives almost maximum thrust with relative large lift force. Although the lift force depends largely on the resistance of conductor at the same mechanical clearance, the thrust is less dependent.

Characteristics for Five Arrangements of Magnets

Figure 26 shows the relation between the measured lift force per driving power and the overlap factor for five magnet wheels shown in Figure 8. Although there is some scatter in the measured values with small overlap factor of 0.7 or less, the lift force per driving power is almost independent on the overlap factor and the arrangement of magnets.

Figure 27 shows the relation between the transformation rate for thrust and the overlap factor. The transformation rate at the overlap factor of 0.66 is about 0.5, this means that the wasteful drag torque is about 50% utilized for the thrust. There is a little difference for the arrangement of magnets.

Figure 28 shows the lift force and the thrust with respect to the total volume of magnets for five partial overlap type magnet wheels respectively. The overlap factor, the mechanical clearance and the revolving speed are fixed at 0.66, 15mm and 11.3m/s respectively. Both lift force and the thrust vary as about 4/3 power of the magnets volume as well as the lift force characteristics for the state of parallel rotation shown in Figure 9.

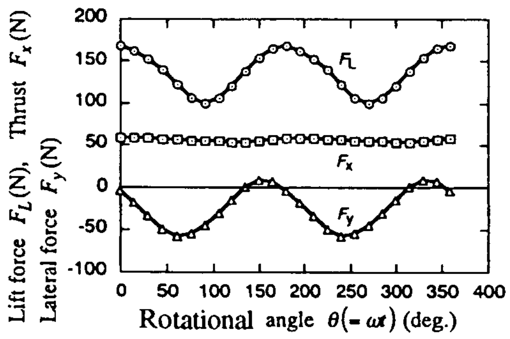


Fig. 23 Fluctuation of forces for rotational angle at the overlap factor of 0.66.

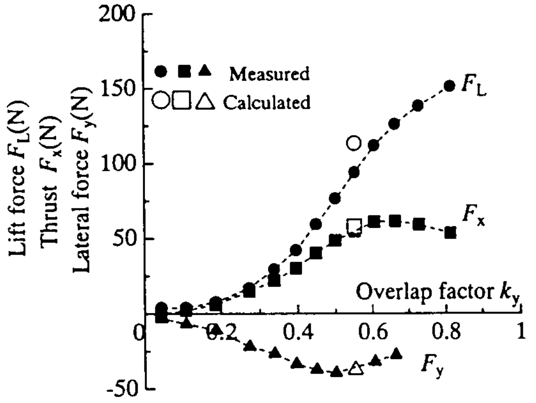
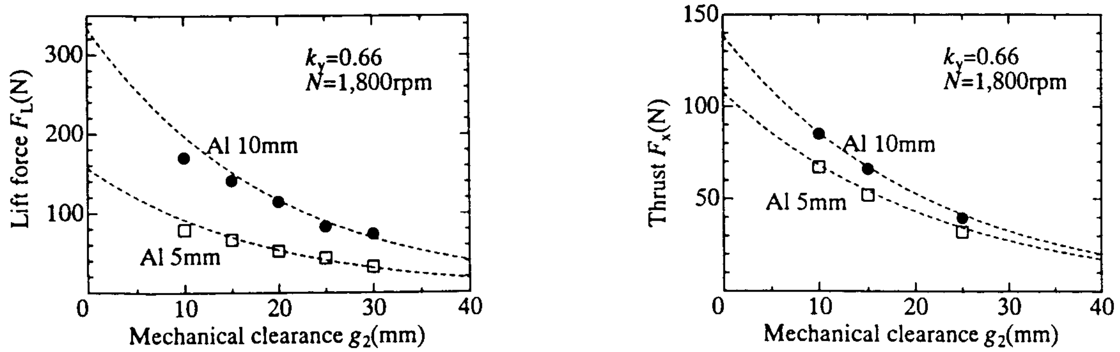


Fig. 24 Lift force, thrust and lateral force - overlap factor characteristics.



(a) Lift force
(b) Thrust

Fig. 25 Mechanical clearance characteristics.

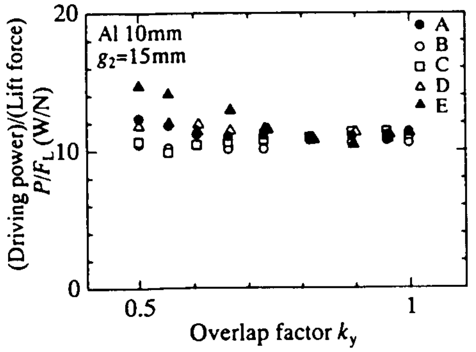


Fig. 26 Lift force per driving power versus overlap factor.

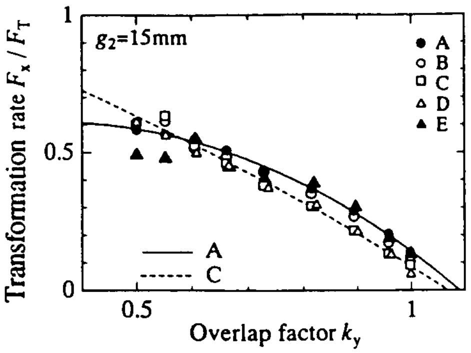


Fig. 27 Transformation rate for thrust versus overlap factor.

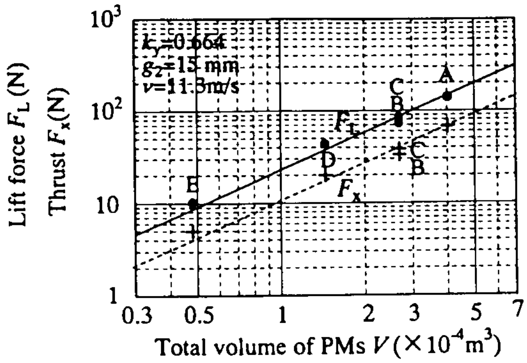


Fig. 28 Measured lift force and thrust for five partial overlap type magnet wheels.

CONCLUSIONS

The following characteristics of the magnet wheel were established;

1. The lift force per driving power doesn't change regardless of the extraction of thrust.
2. The lift force per driving power is approximately proportional to surface conductivity of conducting plate, which is defined as the value of the conductivity multiplied by the thickness.
3. The lift force per magnets volume is approximately proportional to the fundamental factor of mmf distribution of magnet poles. That is, the space harmonics are hardly effective to increase the lift force without increase of power loss.
4. The lift force and thrust are proportional respectively to about 4/3th power of magnets volume.

ACKNOWLEDGMENTS

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