Forces of Magnet Wheels with PMs of Various Sizes

N. Fujii*, K. Ogawa**, K. Ohmija*, M. Chida*, T. Matsumoto***

* Department of Electrical and Electronic Systems Engineering,
Graduate School of Information Science and Electrical Engineering,
Kyushu University, Hakozaki 6-10-1, Fukuoka, 812-81, Japan
Tel: +81-92-642-3914; Fax: +81-92-631-2790; E-mail: fujii@ees.kyushu-u.ac.jp
** Department of Production Systems Engineering, Faculty of Engineering,
Oita University, Dannoharu 700, Oita, 870-11, Japan
Tel: +81-975-54-7799; Fax : +81-975-54-7790; E-mail: ogawa@cc.oita-u.ac.jp
*** Faculty of Education, Saga University, Honjo 1, Saga, 840, Japan
Tel: +81-952-28-8370

Abstract: To research a optimal "magnet wheel", which had proposed by the authors as a new type electromagnetic device with both magnetic levitation and linear drive function, five magnet wheels with various arrangements and sizes of permanent magnets are examined. As the results, magnet wheel with bigger magnets has better performance, and the construction with properly large number poles is favorable.

1 Introduction

There are many magnetic levitation or propulsion techniques including the use of electromagnets, permanent magnets or super-conductors. The authors had proposed the "magnet wheel" as a new type of actuator with both magnetic levitation and propulsion function[1],[2]. The primary member of magnet wheel has high density permanent magnets (PMs) which have developed highly in Japan. A conducting plate is used as the secondary member.

In general, when all the polar faces of the PMs are parallel and uniformly opposite the conducting plate and the PMs are rotated, levitation force and a drag torque along the rotating direction are produced. Due to this torque, corresponding amounts of power loss cannot be avoided. But although it may appear that the electrical resistance of the conductor is almost useless in the use of the levitation force, this resistance is capable of providing a moderate electrical time constant which stabilizes levitation and improves magnetic damping.

In order to effectively make use of the secondary resistance to obtain a levitation force at the same time a propulsion force, two type of permanent rotators had proposed, which are called "tilt type" and "partial overlap type" magnet wheel respectively.

Both types attempt to produce uneven air gap magnetic flux density distribution in the rotating direction. This uneven distribution will produce to a propulsion force and a lateral force in addition to the lift force.

The magnet wheels have following strong points:

(1) Being a self-stabilizing induction repulsive type magnetic levitation, induction type propulsion and guidance force of the magnet wheels, complicated control is not necessary for a magnetic levitation mover.
(2) The magnet wheel gives a possibility to realize a plus payload system in induction type of repulsive magnetic levitation, in where the payload is defined as a subtracting value of the weight of mover from the lift force. Because the structure of the levitation and propulsion is simple, and the rare earth permanent magnets are used which produce a strong magnetic field with compact and light one.
(3) When ac electromagnets are used to obtain repulsive force, large capacity is required because of extremely poor power factor. In the magnet wheels, although the mechanical rotation leads a large weak point, but in the case the mechanical rotation leads enable the operation free of poor power factor. Because magnetic field is not directly by ac windings and only effective power is required to be supplied to rotate the PMs in the armature windings of the driver. Moreover, unnecessary copper loss are avoided because the handling of a large apparent power is not needed. That is, the magnet wheel's capacity and the capacity of the driving source can be brought down to smallest possible value.
(4) This type enables the magnetic levitation at low speed movement, including stationary state.
(5) In running condition, the obtained thrust contributes to improve the total efficiency in the system. Because the thrust is obtained from the

power loss for the lift force.

In this paper, force characteristics for magnet wheels with various PM arrangements and sizes are examined. In the magnetic bearings, the relation between pole arrangement and loss had already examined[3][4]. In the magnet wheel, however, as the drag torque accompanied power loss is made use as thrust (propulsion force), the evaluation is different. The lift force or thrust per PMs volume related to the weight of magnet wheel is most important factor. The better size or arrangement of PMs for magnet wheel is discussed.

2 Basic construction of the magnet wheels

Fig. 1(a) shows the "tilt type" magnet wheel where the PMs' rotator (henceforth to be referred to as "magnet wheel" unless otherwise stated) is inclined to the conducting plate such that is varying air gap. Whereas Fig. 1(b) illustrates the "partial overlap type" magnet wheel where the magnet wheel is made to rotate near the edge of the conducting plate, so that the rotation region of the PMs partially superimpose the secondary conductor.

The poles of PMs are arranged alternately in the rotating direction. The flux linkage in the secondary conductor varies with time by rotating the PMs mechanically. In both types the air gap fluxes and the induced currents in the conducting plate do not distribute uniformly respectively in the rotating direction, so the unbalanced torque produces the thrust component.

The rotating mechanism of the PMs is not illustrated in Fig. 1, but by just placing the armature windings into magnetic flux path of these PMs, a PM type synchronous motor can be constructed too.

3 Tested magnet wheels of various PM arrangements and sizes

Type A, B and C have installed several PMs with the same unit, which thickness is 40mm in the direction of magnetization, on the diameter of 120mm as shown in Fig. 2. The PM is a

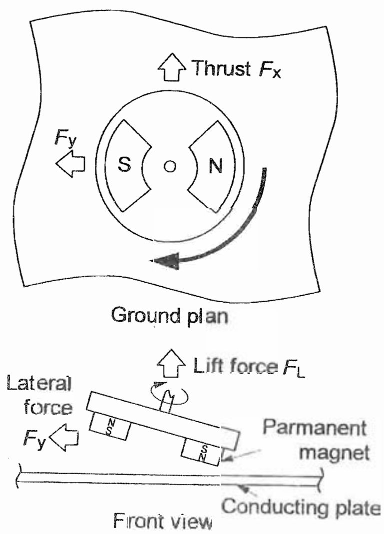


Fig. 1(a) Fundamental configuration of the "tilt type" magnet wheel

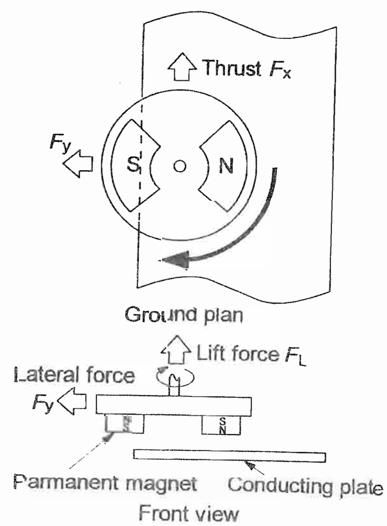
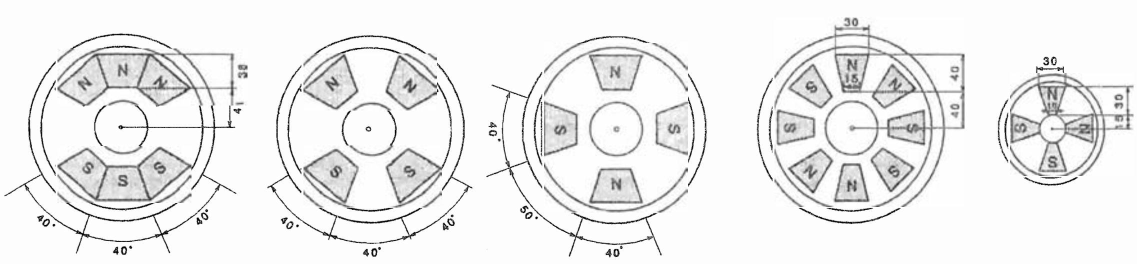


Fig. 1(b) Fundamental configuration of the "partial overlap type" magnet wheel



(a) Type A (b) Type B (c) Type C (d) Type D (e) Type E

Fig. 2 Magnet wheels with permanent magnets of various sizes.

neodymium type rare earth magnet with *iHc* of 11,640Oe and $(BH)_{max}$ of 43.3MGOe.
Type A has two poles and each pole is formed with the three PMs.

Type B has the magnet arrangement lacked a center magnet of the pole of Type A. So, the number of poles and the pole pitch are equal to those of Type A respectively. The PMs volume of Type B is 2/3 times as much as the Type A. The N, N, S, S arrangement of Type B includes large space harmonics component in the rotating direction of PMs flux distribution.

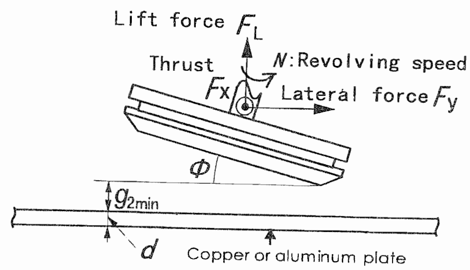
Type C is four-pole arrangement using the PMs of Type B. The volume of magnet wheel is equal to that of the B. The pole pitch is half of that of Type A or B.

In Type D or E the thickness in the direction of magnetization of PM is 20mm which is half of that of Type A-C. The material is the same of the A-C.

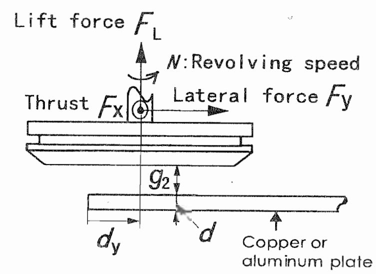
Type D has four-pole arrangement on the diameter of 120mm. The D has half equivalent magnetomotive force and larger space harmonics in the PMs' flux distribution, compared with Type C. The number of poles and the pole pitch are equal to the C.

The diameter of Type E is half of the others. The PMs are arranged in two-pole on the diameter of 60mm. So the E is smaller type of the B. The pole pitch of the E are equal to that of the C or D.

The total volumes of PMs of Type A, B, C, D and E are 4.01, 2.68, 2.68, 1.44 and 0.48 $\times 10^{-4}$ m^3 respectively. So PMs volume of the A, B, C and D are 8.35, 5.58, 5.58 and 3.0 times as much as that of the E, respectively



(a) The tilt type



(b) The partial overlap type

Fig. 3 Main parameters of magnet wheels.

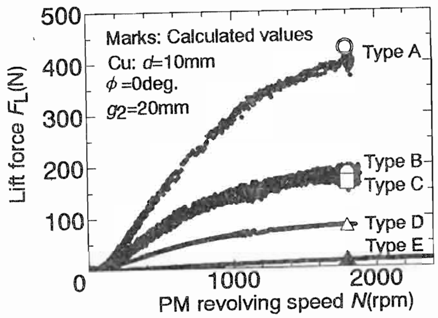
4 Force characteristics

4.1 Parameters of the magnet wheels

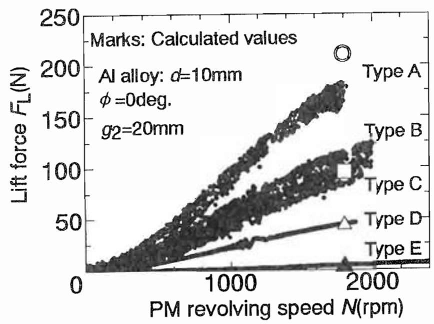
The force of magnet wheel are shown by decomposing into lift force F_L, thrust F_x and lateral force F_y as shown in Fig. 3. In the tilt type, the tilt angle is designated by ϕ, $g_{2\min}$ denotes the minimum mechanical clearance between the surface of conducting plate and the cover of magnet wheel, as shown in Fig. 3(a). The "horizontal position" called in the following means the tilt type with the condition of $\phi=0$, that is the same as a conventional equipment. In the partial overlap type, the lateral displacement is represented by d_y which is defined as the distance of the axis of magnet wheel from the edge of the conducting plate, as shown in Fig. 3(b). g_2 denotes the mechanical clearance between the surface of conducting plate and the cover of magnet wheel which thickness is 3mm. The revolving speed of magnet wheel is represented by N rpm (revolutions per minute). Aluminum alloy (Al alloy, type 2017 T4, the resistivity is 2.94 times as large as copper) or copper (Cu) plate with thickness of d is used as the conductor.

4.2 Lift force characteristics

Fig.4 shows lift force - PM revolving speed curves for five kinds of tilt type magnet wheels called A, B, C, D, E respectively at the horizontal position. Fig. 4(a) and (b) are characteristics for copper plate and aluminum plate respectively. In the figures, solid lines drawn with by dots denote experimental values measured using test facility [1], and marks of ◎, ○, □, △, and ▲ denote calculated values for Type A, B, C, D and E magnet wheel respectively by three-dimensional electromagnetic numerical analysis [1]. The difference in types of magnet wheels has been made clear by both measured and calculated results.



(a) Copper plate



(b) Aluminum plate

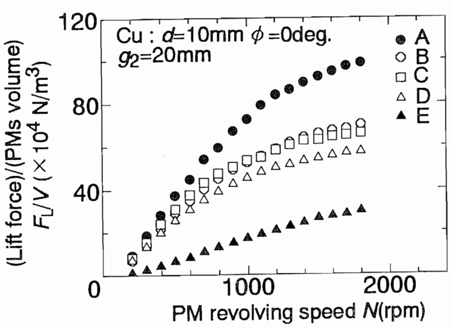
Fig. 4 Lift force for each magnet wheel type at horizontal position

4.3 Lift force per PMs volume characteristics

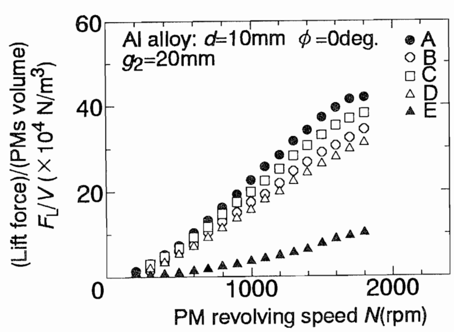
Fig. 5 shows expression in lift force per PMs volume in place of characteristics of Fig. 4. The PMs volume V of each type has been given in last of Chapter 3. Type A has best performance, which has largest fundamental component in the rotating directional distribution of equivalent magnetomotive force of PMs. On the Type E, which diameter is half compared with other type's, when it has the same moving speed of PMs as other's, the lift force will be k ($1.0 < k < 2.0$, $k \approx 2.0$ for aluminum alloy plate) times as large as the value shown in figure. In copper plate, the saturation appears in the characteristic curves of Type C and D with four-pole in lower revolving speed compared with other types, because the frequency of induced eddy current in the conducting plate is two times as much as other types.

Fig. 6 shows lift force per PMs volume versus mechanical clearance characteristics for the type A-E at the horizontal position. The lift forces of Type C, D and E with shorter pole pitch decrease larger respectively as mechanical clearance increases, compared with Type A.

Fig. 7 shows lift force characteristics of the tilt type magnet wheel for the five types. The tilt angle and

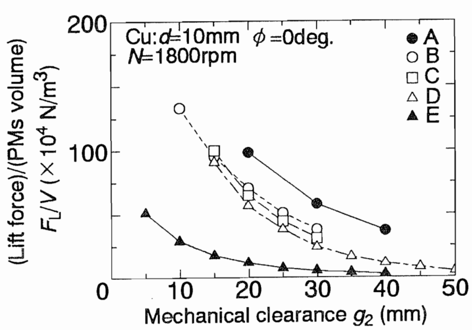


(a) Copper plate

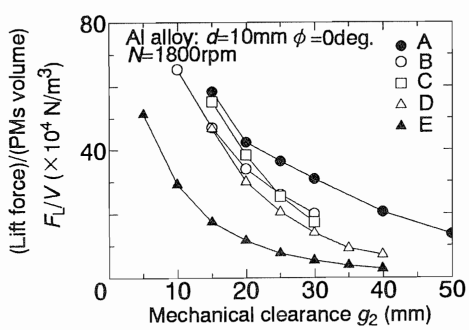


(b) Aluminum plate

Fig. 5 Measured lift force per PMs volume - PM revolving speed characteristics for each magnet wheel type at horizontal position.



(a) Copper plate



(b) Aluminum plate

Fig. 6 Measured lift force per PMs volume - mechanical clearance characteristics for each magnet wheel type at horizontal position.

minimum mechanical clearance were fixed at 10 degree and 10mm respectively. Comparing with Fig. 5(b) at horizontal position, the lift force of Type C and D with half pole pitch of Type A, B decrease slightly respectively. In this condition, Type B has almost same lift forces as Type C although there are differences in the pole pitch and space harmonics.

Fig. 8 shows lift force characteristics for the partial overlap type with lateral displacement $d_y = 0$. Type C with four poles have larger forces compared with values shown in Fig. 5(b).

4.4 Thrust per PMs volume characteristics

Fig. 9 shows thrust per PMs volume versus PM revolving speed characteristics of the tilt type magnet wheel for five types of A-E in the same condition as that in Fig. 7. Type C with four-pole has largest thrust.

Fig. 10 shows thrust per PMs volume characteristics of the partial overlap type in the same condition as that in Fig. 8. Type C and D with four-pole have large thrust.

4.5 Comparison between types of A-E in normalized lift force

In Fig. 11, the longitudinal axis is expressed by normalized lift force which is given as a ratio of lift force of a type to the lift force of Type E, and the horizontal axis is expressed by normalized volume of PMs which is given as a ratio of a PMs volume of a type to the PMs volume of Type E. For example, the denotation of A/E means that the relative lift force is (lift force for Type A)/(lift force for Type E) and the relative volumes of PMs is (PMs volume of Type A)/(PMs volume of Type E). These measured values are almost independent on the revolving speed. In the figures, broken line shows the line of the case that the lift force is in proportional to the volume of PMs. The dotted line shows curve of the case that lift force varies as 4/3th power of the PMs volume. This is the relation between the output power or torque and size in general electrical machines when the temperature rise limit is not considered. In the aspect that the lift force is function of PMs volume, the lift force varies as higher than 4/3th power of PMs volume in each type of magnet wheel.

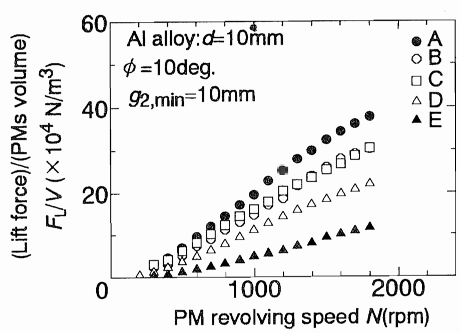


Fig. 7 Measured lift force per PMs volume - PM revolving speed characteristics for the "tilt type" magnet wheels.

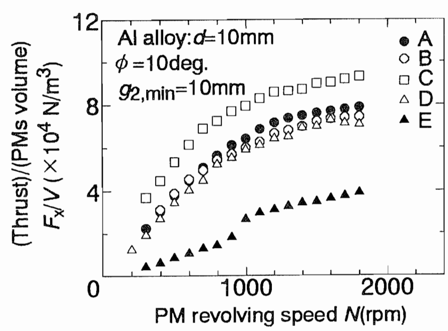


Fig. 9 Measured thrust per PMs volume - PM revolving speed characteristics for the "tilt type" magnet wheels.

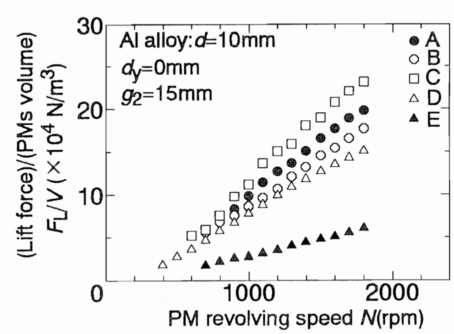


Fig. 8 Measured lift force per PMs volume - PM revolving speed characteristics for the "partial overlap type" magnet wheels.

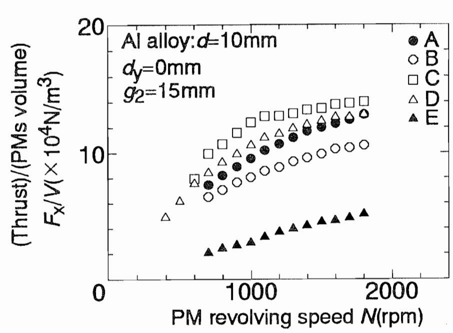


Fig. 10 Measured thrust per PMs volume - PM revolving speed characteristics for the "partial overlap type" magnet wheels.

4.6 Comparison between types of A-E in normalized thrust

Fig. 12(a) and (b) are thrust characteristics at the same condition of Fig. 11(b) and (c) respectively. These figures show that the thrust of magnet wheel varies as about 4/3th power the PMs volume.

5 Conclusions

The above results give the following facts,

1. The repulsive lift force is hardly affected for space harmonics of flux distribution.
2. The magnet wheel with adequate large number of poles (four poles in the test region) has large lift force and thrust, except the lift force of the tilt type.
3. The lift force varies as higher than 4/3th power of PMs volume.
4. Thrust of magnet wheel varies as about 4/3th power the PMs volume.
5. Bigger PM is favorable for the magnet wheel.

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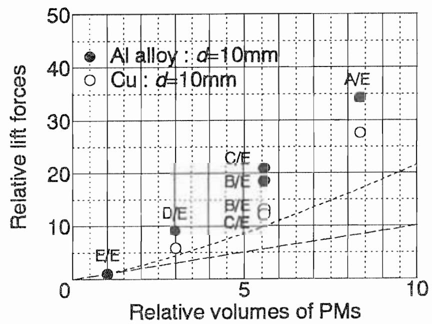
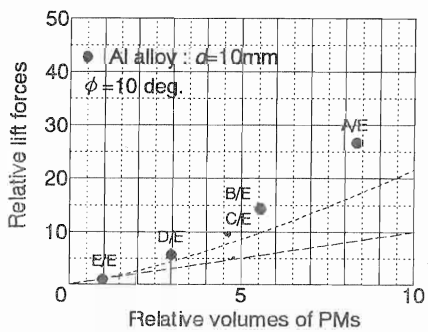
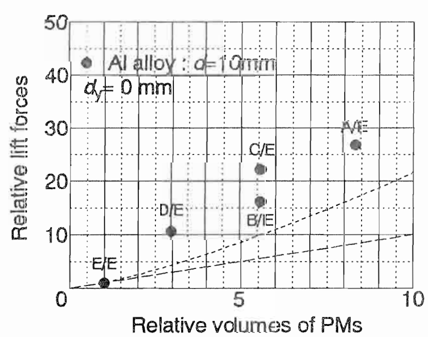


(a) Horizontal position

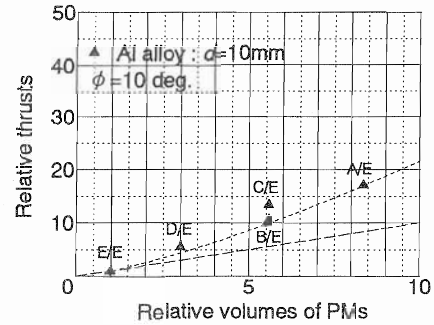


(b) The tilt type

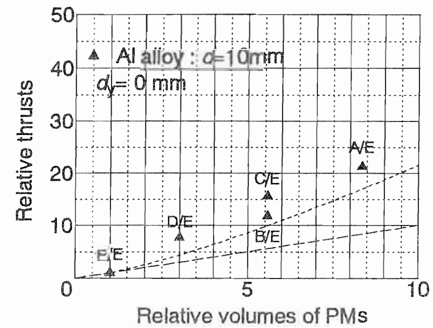


(c) The partial overlap type

Fig. 11 Normalized lift force versus PMs volume.



(a) The tilt type



(a) The partial overlap type

Fig. 12 Normalized thrust versus PMs volume.

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