EXPERIMENTS OF A VERY SIMPLE RADIAL-PASSIVE MAGNETIC BEARING BASED ON EDDY CURRENTS

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ABSTRACT
We developed a very simple new-type passive radial magnetic bearing system which consists of an axi-symmetric magnetic gap and a spinning copper disc inserted in the gap. Restoring radial forces are generated by interaction between eddy currents due to radial displacement of the disc and magnetic flux of the gap. Most important feature is no drag force and no heat problem during no radial displacement of the disc. Main purpose of the experiment was to determine how much the copper disc peripheral of the rotor should be inserted in the magnetic gap of the stator. Results concerning radial restoring component force and its perpendicular one vs rotational speed were shown. Approximate analysis of distributed eddy currents using distributed-parameter model was given.

1. INTRODUCTION

A passive magnetic bearing using AC-electromagnets succeeded to support a short rotor [1]. Supporting force is repulsion due to eddy-currents induced in the rotor. However, heat generated by the eddy-currents was the most serious problem for practical use. Several years ago, we succeeded to levitate wholly passively a spinning rotor whose weight is 7.5[kg] within 0.5[mm] in three dimensional directions using only permanent magnets without any a.c. power source [2].
At that time, as the passive radial magnetic bearing, we adopted laminated coils in which a number of thin null-flux printed coils are put together. They were very expensive. After that, we devised a very simple new-type passive radial magnetic bearing system which consists of an axi-symmetric annular magnetic gap and a copper disc inserted in the gap. No A.C. power source is required. Instead, mechanical touch down bearings are required at

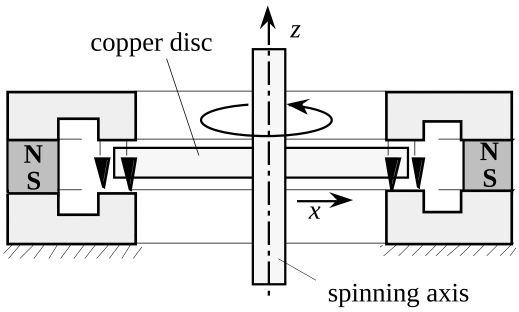

Fig.1 Structure of tesed passive radial magnetic

low rotational speed where eddy currents are very weak and adequate restoring forces can not be obtained. Most important feature is no rotational drag force and no heat is generated if the rotor spins at a symmetric or center position.
In this paper, structure, principles and experimental data of the proposed bearing are given. After discussion about the experimental data, and rough analysis of current distribution using distributed-parameter model, some improvement methods are proposed. However, stability or restoring force of rotational direction or z-axis in Fig.1 will be untouched in this paper.

2. STRUCTURE AND PRINCIPLES OF PROPOSED MAGBETIC BEARING

As shown in Fig.1, the proposed bearing structure is very simple : an axi-symmetric copper disc is rotor side, and its peripheral part is inserted in the annular magnetic gap which is formed by two pole pieces of stator side. D.C. magnetic flux is generated by an annular permanent magnet. No electric power source is required. Instead, mechanical touch down bearing is requierd at low rotational speed.

Apparently, they construct a kind of magnetic eddy current damper, though relation between stator and rotor is opposite. Most important feature is no drag force is generated if the rotor spins at a symmetric position or there is no radial displacement of the spinning rotor. Because of symmetry, e.m.f. generated at all inserted peripheral part of the copper disc are also symmetric. Therefore, as long as the symmetry is maintained, no eddy current, accordingly no rotational drag torque, is generated in the copper disc.
If the rotor displaced from the symmetric position, eddy currents begin flowing. As the inserted part is relatively narrow, the eddy currents form multiple narrow loops and may have crescent shapes.
For intuitive explanation, very rough distribution of the multiple loop currents has been analyzed using simplified lumped-parameter model [3]. In this paper, different analysis using distributed-parameter model was tried in the later discussion section.
The distributed eddy currents have short radial parts and relatively long circumferential parts. They interact with the magnetic flux density of the gap : the former generates drag forces whereas the latter radial ones. The inserted part of the disc is sandwiched by two iron pole pieces, therefore, their electric character will be strongly inductive and rather weakly resistive. At high rotation speed, this means the eddy currents have large time constants which delay peak flow of each eddy current from the instant each current loop generates each e.m.f..
If there is no phase lag, then total eddy current force becomes perpendicular to radial displacement direction.
The total drag forces are not necessarily symmetric to the rotation axis. Therefore, they can be decomposed to pure drag torque and radial forces. Resultant radial force includes not only a restoring force but also a perpendicular component which should be decreased.

3. SHAPE AND SIZE OF EXPERIMENTAL MAGNETIC BEARING

Figure 2 shows sectional shape and size of the bearing for experiments. An annular permanent magnet with two annular pole pieces, forming C-shaped cross section and providing an annular gap, was stator side, and one of three different sized copper discs inserted in the annular gap was rotor side . The three sizes were ϕ43, ϕ46, ϕ48 in outer diameter, whereas the inner edge of the gap was ϕ42, therefore, inserted radial length of each disc was 0.5, 2.0, 3.0[mm], respectively. In Fig.2, ϕ46 disc is installed as an example. The gap distance is 3[mm], and thickness of the all disc is identically 2[mm], which means clearance is 0.5[mm] on both sides of each disc.
In experiments, the magnet with pole pieces was mounted on a movable stage in order to change relative radial

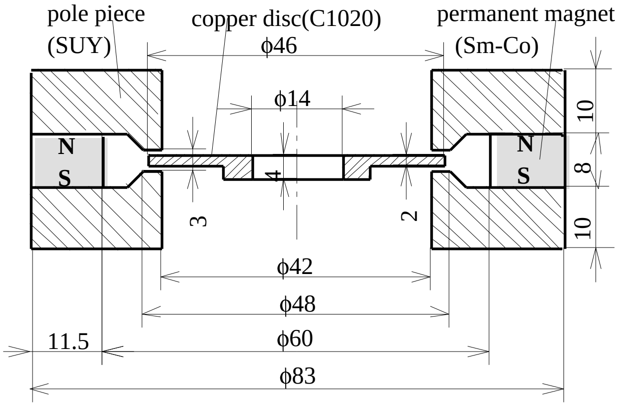

Fig.2 Dimensions of magnetic circuit and a copper disc

displacement x., whereas disc shaft was immovable. A force measuring system was fastened between the movable stage and the magnet system, and supplied measured signals of restoring force F_x and vertical force F_y which was unwanted force. Magnetic flux density of the gap was 0.6 [T] generated by an annular Sm-Co family permanent magnet. As shown in Fig.2, the inner part or magnet-side of pole pieces formed a slope and leakage flux was by far larger there compared to the outside cliff part.

4. RESULTS OF EXPERIMENTS

Restoring force F_x and the vertical or y-directional force F_y versus radial displacement x up to 3[mm] of three discs at a constant rotational speed, 3000[rpm] are shown in Fig.3. In any case, larger disc where inserted radial length becomes larger shows larger values of both F_x and F_y. We can see a tendency of saturation in both F_x and F_y at larger impractical displacements. In practical use, displacement will be less than 0.5[mm] and we can see linearity or constant stiffness up to nearly 1[mm]. More important fact is the stiffness is nearly proportional to disc diameters or inserted radial lengths. The ratio F_x/F_y at 3000[rpm] is about 7~8 and this is the most serious problem to be solved. An idea to this problem will be shown later.
At constant speed of 4000[rpm], almost the same tendencies as the case of 3000[rpm] were obtained, and so, the figures were omitted here.
Figure 4 shows F_x and F_y vs. rotation speed, where radial displacement x was fixed at 1[mm], and the rotational speed was changed from zero to 5000[rpm].
We can see F_y is about linear, whereas F_x has parabolic characteristics, which will be promising at high speed use. The ratio F_x / F_y at 5000[rpm] is about 4, which is nearly a half of 3000[rpm] case.

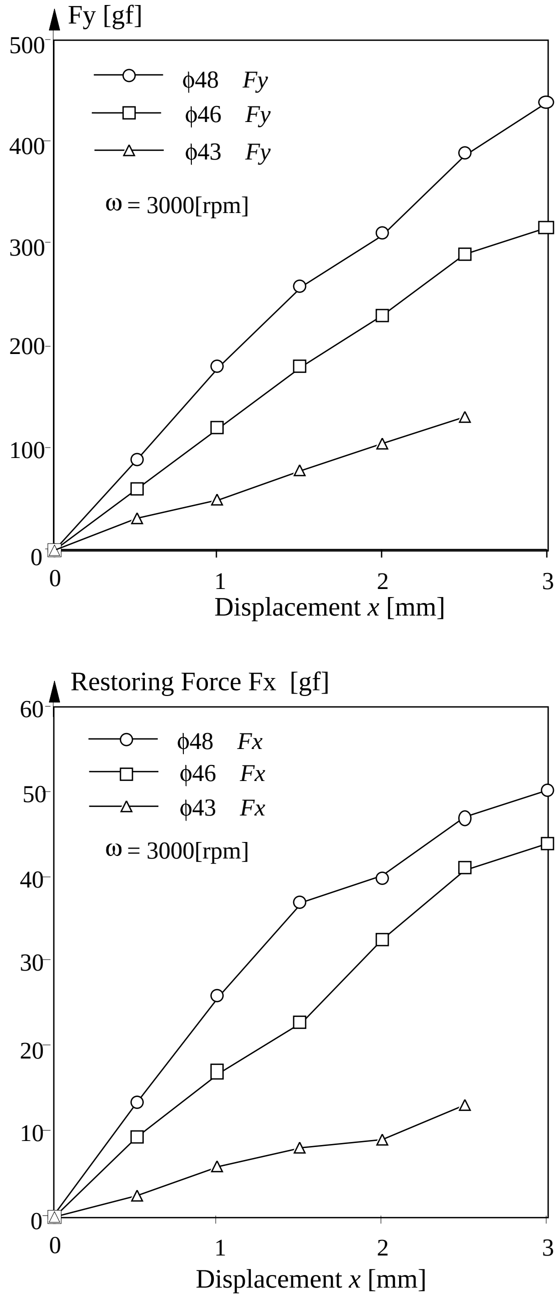

Fig.3 Forces generated by disc displacement x

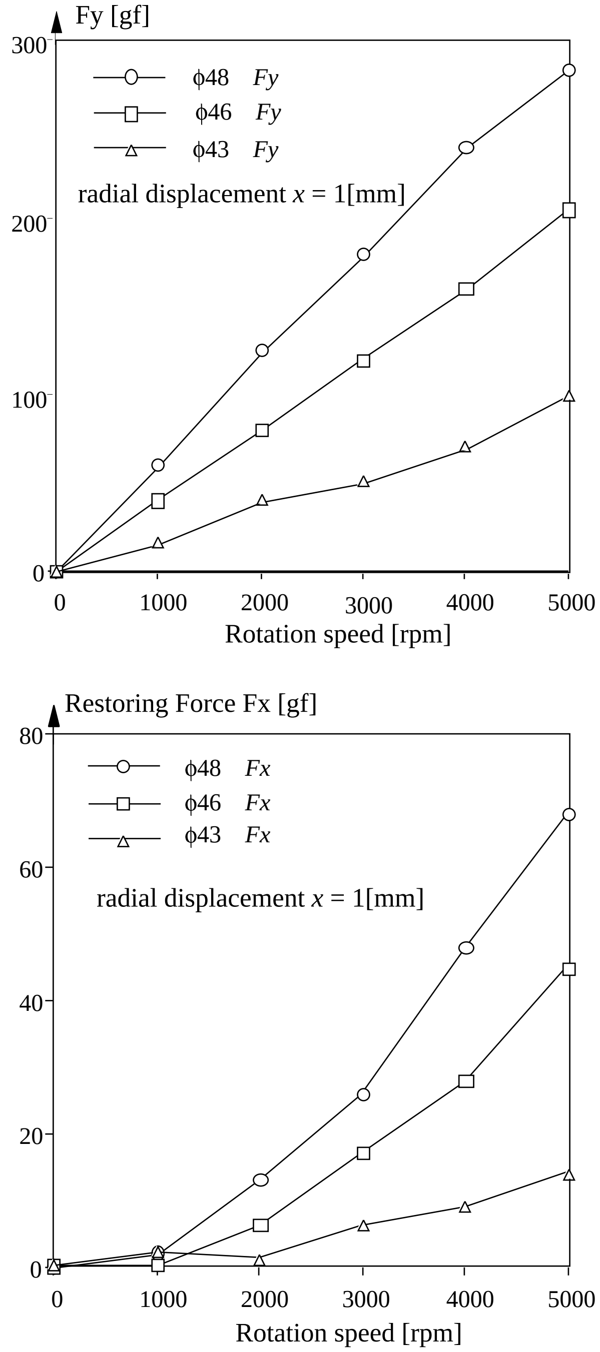

Fig.4 Stiffness to radial displacement vs. rotation speed

5. DISCUSSION

5.1 Approximate Distribution of Eddy Currents

In this section, let's try to obtain rough distribution of currents generated by relative radial displacement x.. To do so, the following simplification is adopted :

1. Magnetic flux density in the gap is constant, B_0 , and outside the gap is zero (leakage flux is zero).
2. Each inserted radial legth of the disc generates e.m.f. due to rotation speed ω and disc radius a .
3. Outside the gap part of the disc is zero impedance.

Referring to Fig.5, inserted length $l(\theta)$ can be expressed as:

$$l(\theta) = a + x\cos\theta \qquad (1)$$

Induced e.m.f., $e(\theta)$, on that part is :

$$e(\theta) = a\omega \times l(\theta) B_0 = a\omega B_0 (a + x\cos\theta) \qquad (2)$$

The θ position at $t = 0$ change $\theta \quad \theta + \omega t$, therefore

$$e(\theta, t) = a\omega B_0 (a + x\cos[\theta + \omega t]) \qquad (3)$$

$$= \bar{e} + \tilde{e}(\theta, t) \qquad (4)$$

where

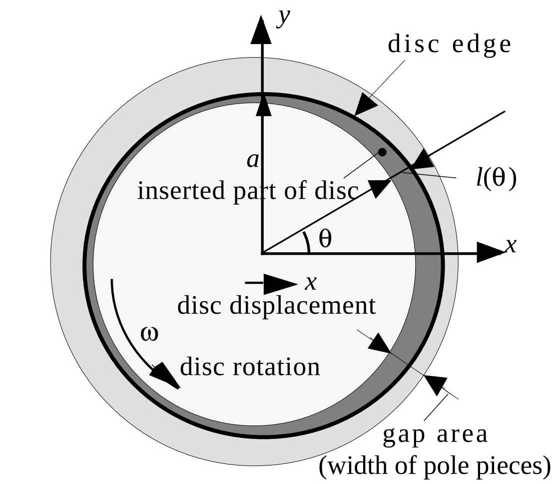

Fig. 5 Asymmetric e.m.f. area due to disc displacement

$$\bar{e} \quad a^2\omega B_0 \cdots \text{D.C.component} \tag{5}$$

$$\tilde{e}(\theta,t) \quad a\omega B_0 \times x\cos[\theta+\omega t]\cdots \text{A.C.component} \tag{6}$$

Supposing an annular shaped ladder model as shown in Fig.6, circumferencially distributed voltage v andcurrent i are governed by the following simultaneous partial differential equations :

$$\frac{\partial v(\theta,t)}{\partial\theta} = \quad Z_c\, i(\theta,t) \tag{7}$$

$$\frac{\partial i(\theta,t)}{\partial\theta} = \{v(\theta,t) \quad e(\theta,t)\}/\, Z_r \tag{8}$$

where Z_c and Z_r are impedances per unit radian of the copper disc along circumferentilly and radially, respectively.

All variables of time are Laplace transformed:

$$\mathrm{L}[v(\theta,t)] = V(\theta,s), \quad \mathrm{L}[i(\theta,t)] = I(\theta,s) \tag{9}$$

$$\mathrm{L}[\tilde{e}(\theta,t)] = \tilde{E}(\theta,s) = a\omega B_0 x\, \mathrm{e}^{(\theta/\omega)s}\mathrm{L}[\cos[\omega t]] \tag{10}$$

where L[ ] means Laplace transformation. In deriving Eq.(10), the transition theorem of time domain is used. Using Eqs.(7, 8), the following 2nd order ordinary differential equation is obtained provided that Z_r is independent of θ :

$$\frac{d^2 I(\theta,s)}{d\theta^2} \quad \frac{Z_c}{Z_r} I(\theta,s) = \frac{1}{Z_r} \times \frac{d\tilde{E}(\theta,s)}{d\theta} \tag{11}$$

$$= \frac{axB_0}{Z_r} s\, \mathrm{e}^{(\theta/\omega)s}\, \mathrm{L}[\cos[\omega t]] \tag{12}$$

What we need is not transient terms but only steady state term generated by forcing term of right-hand side. Assuming the following particular solution :

$$I = P\mathrm{e}^{(\theta/\omega)s} \tag{13}$$

where P is an unknown complex function which includes not θ but Laplacian variable s, and substituting it into

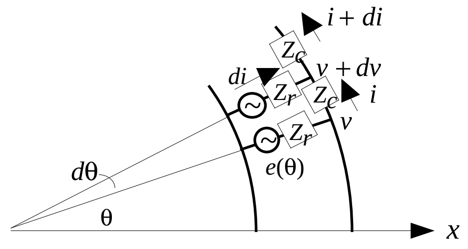

Fig.6 Distributed-parameter model of induced currents.

Eq.(12), we obtain :

$$\left(\frac{s}{\omega}\right)^2 P \quad \frac{Z_c}{Z_r} P = \frac{xaB_0}{Z_r} s\, \mathrm{L}[\cos[\omega t]] \tag{14}$$

$$P = \frac{xaB_0 s}{Z_r(s/\omega)^2 \quad Z_c} \mathrm{L}[\cos[\omega t]] \tag{15}$$

$$I(\theta) = \frac{xaB_0 s\, \mathrm{e}^{(\theta/\omega)s}}{Z_r(s/\omega)^2 \quad Z_c} \mathrm{L}[\cos[\omega t]] \tag{16}$$

In order to get steady state current distribution, $s \quad j\omega$ is required :

$$I(\theta) = \frac{-j\omega\, \mathrm{e}^{j\theta}}{Z_r+Z_c} xaB_0\, \mathrm{L}[\cos[\omega t]]$$

$$= \frac{\mathrm{e}^{j(\theta \quad \pi/2)}}{Z_r+Z_c} \omega xaB_0\, \mathrm{L}[\cos[\omega t]]$$

$$= \frac{\omega aB_0}{Z_r+Z_c} x\, \mathrm{L}[\sin[\omega t+\theta]] \tag{17}$$

As the denominator, $Z_r + Z_c$, of Eq. (17) is an impedance, the rest or numerator of Eq. (17) is dimensionally equivalent to distributed e.m.f..

If, $Z_r + Z_c$ is pure resistive, then the circumferential currents distribute sinusoidally : maximum positions are $\theta = \pm\pi/2$ or intersecting positions with y-axis. However, $Z_r + Z_c$ is rather inductive, because both Z_r and Z_c are sandwiched by two pole pieces, therefore a phase lag occurs : the maximum currents flow after passing some phase lag angle ψ where the maximum positions move to second and fourth quadrant approaching to $\pm x$-axis.

Radial directional currents are easily obtained : gradient of Eq.(17) is solution. If $Z_r + Z_c$ is pure resistive, then maximum current densities occur at $\theta = 0, \pm\pi$ or intersecting positions with x-axis. Influence of the phase lag angle ψ is quite identical with the former case.

Figure 7 shows rough distribution of eddy currents using only six loops, where the maximum current density points of both radial and circumferential components, x- and y-axis, in case of $\psi = 0$, transfer to x- and y-axis points with phase lag angle ψ . Currents outside the gap

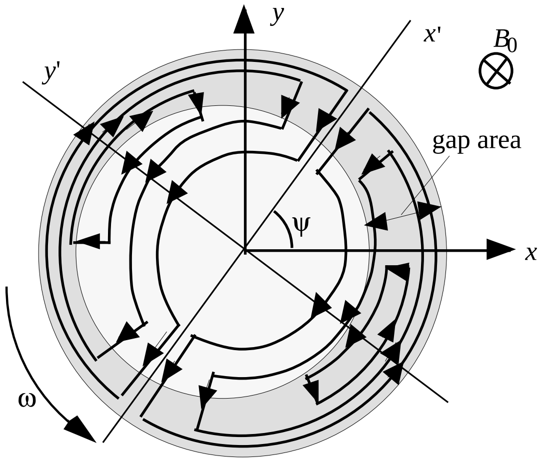

Fig.7 Eddy currents distribution with phase angle ψ

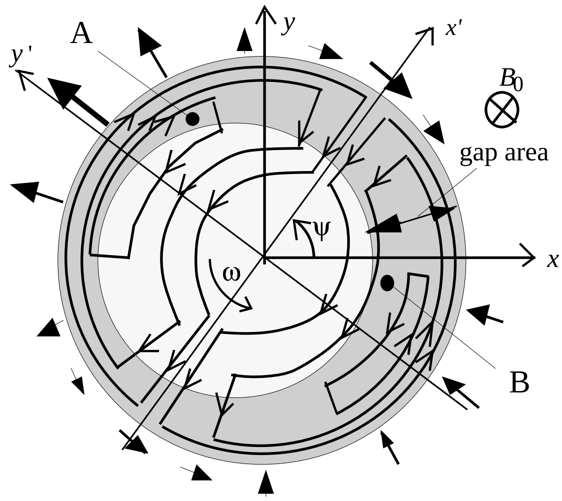

Fig.8 Distribution of induced force due to x-directional displacement of disc

area or near the central part of the disc have little meaning, because that area be supposed to be zero impedance and to be free from magnetic flux. The dark gray area in Fig.7 (shown as gap area) means the inserted or sandwiched part of the copper disc. At the instant the currents become maximum, a very important matter is whether they are included or not in that area.

5.2 Forces Generated by Eddy Currents

The distributed currents interact with magnetic flux to generate forces F due to the theorem of right hand or the following vector product :

$$F = I \quad B_0 \tag{18}$$

As mentioned earlier, the peak currents flow with time lag or phase lag shown as ψ in Fig.7 to the instant each current loop generates each e.m.f. . Some currents may move to outside the gap or zero magnetic density area. These currents generate no force.

Let's consider the distribution of circumferential currents somewhat in detail. Of course, the e.m.f.s are generated at B_0 area. The circumferential currents flow not neccessarily edge part of the disc. They distribute radially almost homogeneously as shown Fig.7, 8. Apparently radial inserted length $l(\theta)$ of Eq.(1) seems to be proportional to F. This is not correct, because small l part may be accompanied with returning or opposite directional currents nearby outside initially, and they may be included in new wider l region and therefore may generate opposite force. On the other hand, large l part may lose effective currents to the outside, but include no opposite currents as it moves to small l region. For example, see two points A and B in Fig.8, which are symmetrical positions to x axis, but their l s are different : the former is shorter. The former has nearly three effective currents in the shorter l whereas the latter has only one effective ones, as two are cancelled.

Radial currents appear to have no opposite current problem. In practice, small l region moves to wider l region keeping the length of radial currents almost constant, because initial nearby outside currents may be almost returning circumferentil one. Of course, when large l part moves to smaller l current region, some length of radial currents may forced out from new l region.

In any case, larger e.m.f. regions generate larger forces when they move to smaller l region compared to the case of opposite conditions. Specifically, two representative forces are generated by the third quadrant circumferential currents and the first quadrant radial ones. Detailed analysis is beyond this paper, and distribution of several representative forces generated by both circumferential and radial currents are shown using arrows in Fig.8.

6. A PROPOSAL FOR PASSIVE RADIAL MAGNETIC BEARING

As already shown, radial components of eddy currents generate unwanted canceling forces. More inductive and less resistive structure of the disc is preferred. It is clear from Fig.3 and 4 and given rough analysis that thicker copper disc and wider gap width or large l keeping large B_0 are indispensable in order to obtain large restoring force, F_x. This means strong magnets and large gap volume filled with large magnetic energy are required.

Figure 9 is a proposal to satisfy the above-mentioned requirement. The most important structural improvement is electrical insulation of the copper disc. The insulation is set up at about center of pole piece width, and the copper disc become two discs : outside and inside ones.

Downward figure of Fig.9 shows the case of x-directional displacement of the rotor where directios of maximum radial currents of both outside and inside parts are opposite each other, therefore above-mentioned unwanted forces may almost canceled out, though as drag torque, they are summed up. In this figure, ψ -rotation are omitted to avoid complication. It is easy to understand that circumferential currents are the same direction : forces of both discs are summed up as shown in Fig.9.
In Fig.1 or tested model, passes of returning currents are nearly resistive with little inductive characteristics. In the proposed one, copper disc with H-shaped cross-section is adopted. The returning passes are now by far inductiove which will be very effective for gaining larger phase lag angle ψ even at low speed. In high speed, perhaps we can expect faster approaching to 90[deg] of ψ .
However, perfect 90[deg] of ψ will be difficult, meaning some amount of vertical components may be unavoidable. An idea to this problem is to use spot magnets which are set at near the outer surface of the disc, for example, four magnets are set on $\pm x, y$ axes positions. The effects of the spot magnets are spot drag forces whose acting points of the disc do not chage their positions due to ψ . This means the directions of the spot drag forces are always perpendicular to the displacements.
The main drag force of the first quadrant in Fig.8 is opposite to the second quadrant one. However, in Fig.9, the outer copper 's main drag force shown left side is the same direction to the main circumferential current force shown bottom. Here, only outside copper disc with only outer flange and spot drag forces may be sufficient.

7. CONCLUDING REMARKS

1. A novel passive magnetic bearing was proposed. very simple, without a.c.power source.
2. Experimental data of both restoring and the perpendicular forces were given.
3. Approximate distribution of eddy currents were analytically given using distributed-parameter model.
4. From experimental and analytical results
   - only circumferential currents are usefull but radial ones have adverse effects.
   - large inserted volume are preferable.
   - large phase lag of eddy currents is effective.
5. An idea of improved structure was proposed based on item 4.
   - an outer-rotor-type copper ring disc was proposed making returning current passes more inductive.

(Superconducting magnets seem to be very effective in this application. This improved model has not been manufactured yet.)

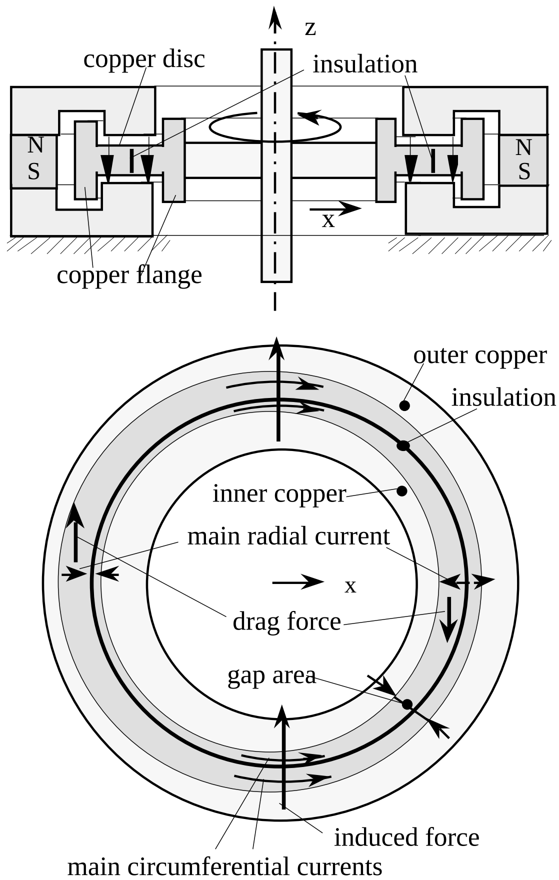

Fig.9 Proposed passive radial magnetic bearing (effects of ψ -rotation are omitted)

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