Principle and Experiments of an All-passive-type Magnetic Bearing System

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Abstract : It has been proved by a toy, magnetically levitated spinning top, that magnetic levitation without active control is possible if the body to be levitated has rotational speed. The authors were also trying developing the titled system. At the first experiments of the system, we could not levitate the rotor due to excessive rotational drag force of eddy currents in the null-flux coil system. That is to say the rotational velocity which was required for levitation could not been attained using air turbines. By stacking many sheets on which many thin coils were printed, an improved null-flux coil system was made and was used in the second experiments. In the second experiments, 6,000 r.p.m. of the rotational speed was attained, and we could levitate the rotor (about 7.5kg) within ± 0.5mm radial and axial air gaps of the touch-down bearings in Feb. of 1995. In this paper, mainly structural/dynamical features, experimental data and its analysis are given.

Key words : Magnetic Bearing, All-Passive, Rotor Dynamics, Sleeping Top, Permanent Magnet, Null-flux Coil, Inductive Current, Eddy Current

1 Introduction

It is well known as Earnshaw's theorem[1] that all-passive-type magnetic levitation using magnetic force of only permanent magnets is impossible. However, if the body to be levitated is rotating, the situation is wholly changed. In other word, Earnshaw's theorem is valid only for statical cases, and not valid for dynamical ones. It has been proved by a toy named "U-CAS", magnetically levitated spinning top (about 30 gramms), that magnetic levitation without active control is possible if the body to be levitated has rotational speed. The authors have been trying to develop all-passive-type magnetic bearing systems[2], and success of levitation (rotor weight 7.5kg) was attained about four months after the toy. In this paper, mainly structural/dynamical features, experimental data and its analysis are given.

2 Magnetic Structure of the System

Vertical or axial levitation forces are derived from not only repulsive but also attractive forces of permanent magnets in order to obtain suffcient levitation force without large unstable radial stiffness as shown later . However, though small, unstable radial stiffness is inevitable in case of all-passive-taype magnetic levitation. To overcome this problem, restoring horizental or radial forces are derived from a electromagnetic induction type null-flux system. The null-flux system cosists of a couple of rotor discs on which many Nd permanent magnets are mounted so that they produce magnetic fields between them, and a null-flux coil disc of the stator in the magnetic fields (see Fig.2 and Fig.5). The magnet discs generate a.c. magnetic fields on the null-flux coils when the rotor rotates. Theoretically, there is no current if the rotor aligns with the center line. Deviation from the center line generates inductive e.m.f. which produces induction currents in the coils, and the currents interacts with the magnetic fields of the gap and becomes stable radial stiffness.

The radial forces generated by above-mentioned null-flux system using conventional permanent magnets are very weak compared to the system using superconducting magnets. Therefore, it is important to make the radial unstable stiffness generated by the permanent magnets, which generates the stable vertical stiffness, small, as the unstable radial stiffness should be smaller than the one generated by the null-flux system for radial stability. This relation is clear from the next formula [3]:

$$K_z + 2K_r = 0 \qquad (1)$$

where K_z is axial or z-direction stiffness and K_r is the radial one of the magnetic forces of naked permanent magnets. To make the levitation stable, both K_z and K_r of the total system should be negative.

In order to obtain large levitation force, F_z, with relatively small K_r, a triplet magnets construction in which a permanent magnet of the rotor is inserted between two magnets of the stator is devised[4]. The inserted rotor part gets two different kinds of levitation forces, i.e., repulsion force from the bottom and attracting one from the upper magnet. Adjusting distance of the two outer stator magnets, the above-mentioned requirements can be satisfied. In other words, main levitation force F_z is obtained from the bottom magnet with relatively large $|K_z|$ and $|K_r|$, on the other hand, the attraction force makes F_z large and both $|K_z|$ and $|K_r|$ small, because its sign of F_z is the same but signs of K_z and K_r are opposite to the bottom or repulsion magnet. Of cource, total K_r of the triplet magnets is positive or unstable which must be cancelled by the null-flux system.

If the two null-flux systems are used at the both end of the center axis, the rotor posesses stable tilting stiffness at high spinning speed. However, in our system, only one null-flux system was used at nearly center part of the system, and two set of the triplet magnets were used at the both end of the center axis. Therefore, the rotor posesses unstable tilting stiffness just like spinning tops independent of rotational speed.

Figure 1 shows an example of measured levitaion force F_z of one set of the triplet magnet, where middle magnet is moved in three different total gap lengths (TG = upper + lower gaps). Each of three magnets consists of double ring magnets with different radius and opposite magnetic polarity. A horizontal dashed line of 3.68kg is one half of planned rotor weight, and its crossing points with the curves of levitation forces are equilibrium points. Of cource, only left side points are stable, because $K_z < 0$ at those points. Ratio of measured value, K_z / K_r = 304[grf/mm]/177 [grf/mm]= 1.72 is considerably smaller than 2 of Eq.(1). Perhaps, this is due to accuracy of measurement system, which has rather weak structural stiffness.

At over some rotating speed which generates stable radial stiffness larger than unstable ones of the triplet magnets, both axial and radial stiffnesses for only translational motions are satisfied. Of course, tilting stiffness is unstable even though at high speed.

The triplet magnets has relatively large space between the rotor and the stator magnets, therefore, relatively large amount of copper can be mounted on the stator magnets neighboring to the rotor magnets to obtain translational damping and nutational or high speed mode damping of the tilting motion. Precessional or low speed mode of the tilting motion requires special dampers which has little effects on the translational motion and has copper on the rotor side[5].

Figure 2 shows the total structure of the system, indicating inner-rotor type one without electric motor. Air turbin method were used for spinning the rotor in order to avoid unstable magnetic forces from electric motor.

3 Null-flux Coil System

As shown in Fig.2, each magnet disc has two lines of Nd magnets which are aligned on two concentric circles. Figure 3 shows principle of the null-flux system using simple model

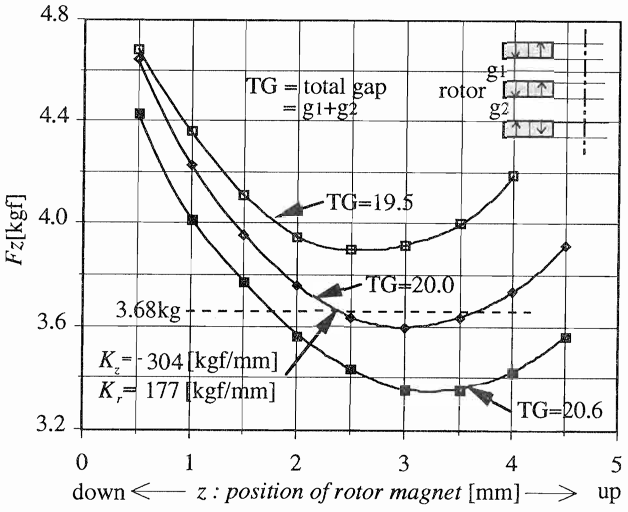


Fig.1 Levitaion Force of One Set of Triplet Magnets

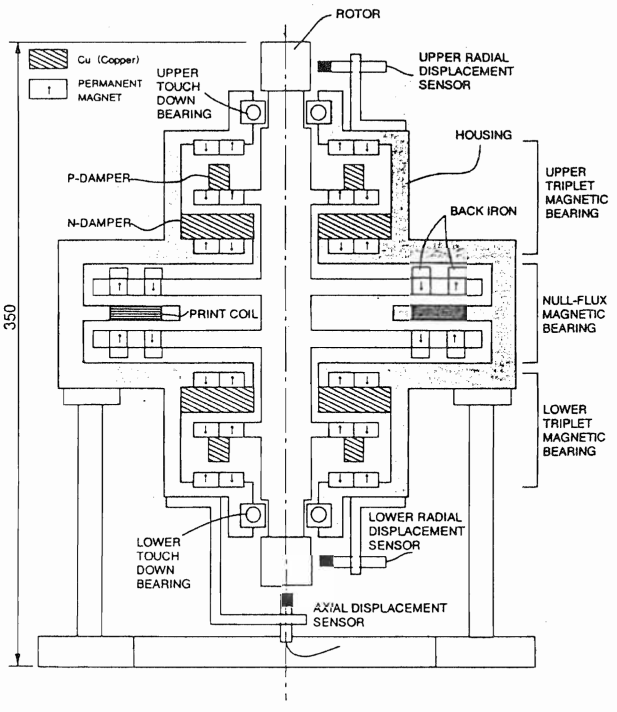
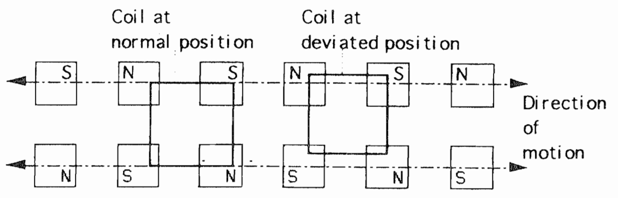


Fig.2 All-passive-type magnetic bearing system



Fiig.3 Fundamental null-flux system using rectangular coil and two lines of magnets

which consists of two straight lines instead of circular lines of magnets and rectangular coils. If, the rotor is center position, total magnetic flux crossing each coil is zero, meaning no e.m.f. is generated in the coil loop. On the other hand, if the rotor deviates from the center position, the total flux is not zero this time, meaning e.m.f. is generated and so induced currents flow with some phase lag or time constant which is determined by electric resistance R and self-inductance L of the coil. This phase lag is indispensable to generate restoring force $\boldsymbol{F}$ which is a vector product of current $\boldsymbol{i}$ and flux density $\boldsymbol{B}$:

$$\boldsymbol{F} = \boldsymbol{i} \times \boldsymbol{B} \tag{2}$$

Initially, we made various shapes of coil out of thin copper sheets. Figure 4 is an example of hexagonal shape coils which were made aiming at improvement of volume occupation rate of copper, and they were set at relatively wide gap (gap length was 11[mm], and the flux density $\boldsymbol{B}$ was $\boldsymbol{B} \fallingdotseq 0.3$[T]) as shown in Fig.5. Figure 6 shows restoring force and drag force of 17 coils which were molded using resin in a compact shape, forming a part of the coil disc. The inclination of the restoring curve is K_r of partial coil disc. The total K_r of whole coil disc must cancel out the above-mentioned unstable K_r of two sets of triplet magnets. After simple calculation, it was found that required rotation speed was about more than 3,500 [r.p.m.].

The curve of drag force describes nearly a parabola : it means drag force is insensitive to the coil displacement unless it takes large value, or the rotor does not suffer large drag change by its displacement. However, it has relatively a large constant value or a bias drag, which became a deathblow to the hexagonal shape coils as follows.

Two hundreds of the hexagonal coils were molded into a coil disc using resin and set between the two magnet discs which were rotated by air turbin. However, the air turbin could not attain the required rotational speed of 3,500[r.p.m.] due to the bias drag or unexpected large eddy currents in the null-flux coils. The maximum ratational speed we could attain was about only 1,000[r.p.m.]: lower than one third of the required one.

To overcome this problem, by far thin coils were required. By stacking 120 sheets on whose both surfaces many thin coils were printed, an improved null-flux coil disc was made and was used in the second experiments. Figure 7 shows outline of the total coils and detail of each coil. In the second experiments, 6,000 [r.p.m.] of the rotational speed was attained

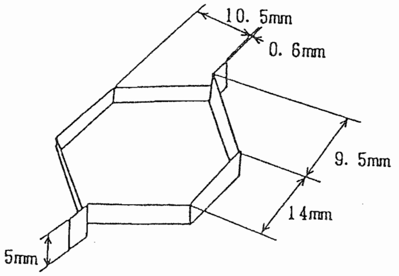


Fig.4 Null-flux coil with hexagonal shape

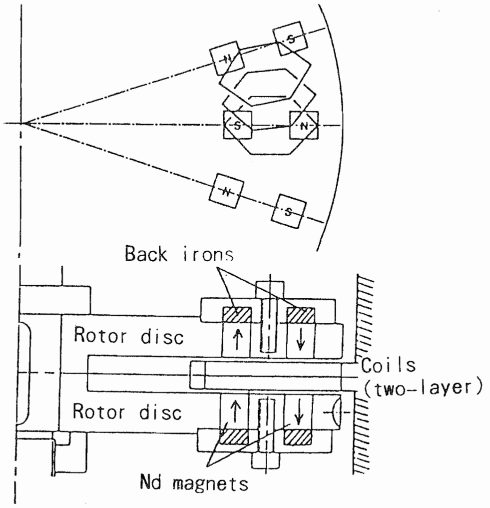


Fig.5 Experimental set-up for null-flux system

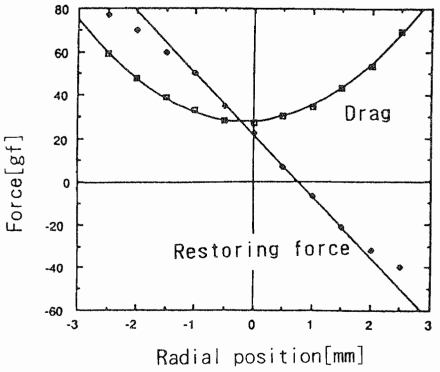


Fig 6 Experimental data of hexagonal coil

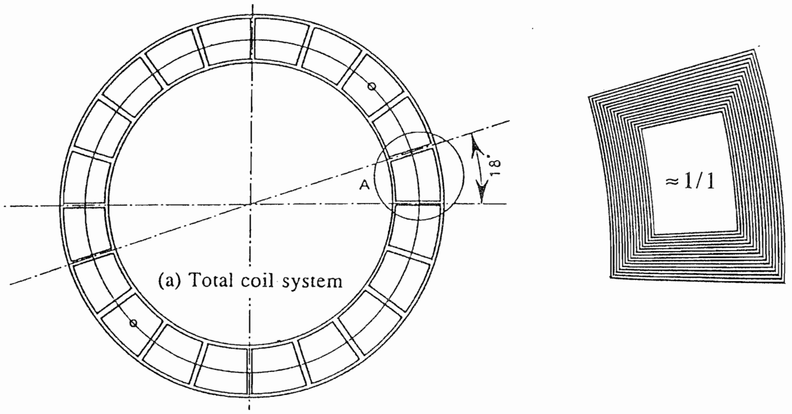


Fig.7 Null-flux coil using printed sheet

4 Dynamics of Levitated Rotor

4.1 Translational Motion

As was already shown, though vertical motion is statically stable, horizontal motion is statically unstable. Rotational speed more than 3,500 [r.p.m.] can stabilize it. Damping of both vertical and horizontal motions are given mainly by coppers of triplet systems which are also nutation dampers of attitude motion and shown in Fig.2 as N-damper. Of course, the null-flux system has weak damping effects, but they will be not discussed in this paper.

4.2 Attitude Motion[2]

Even though given rotational speed more than 3,500[r.p.m.], the rotor has unstable tilting stiffness like a spinning top. Tilting motion of sleeping tops has the following 2nd order complex coefficient characteristic equation:

$$\lambda^2 + (n - \mathrm{j}h)\lambda - (k + \mathrm{j}hp) = 0 \qquad (3)$$

where h and k are spin-axis component of angular momentum vector and tilting stiffness both divided by lateral moment of inertia, respectively. And n and p are nutational and precessonal damping coefficients both divided by spin-axis component of angular momentum vector, respectively, and j is the imaginary unit.

Two eigenvalues, λ_N and λ_P, of Eq.(3) at high speed are:

$$\lambda_N \approx -n + p + \mathrm{j}\{h - (k/h)\} \quad \text{(nutation mode)} \qquad (4)$$

$$\lambda_P \approx -p + (nk/h^2) + \mathrm{j}(k/h) \quad \text{(precession mode)} \qquad (5)$$

For asymptotic stability condition or sleeping top, all real part of the eigenvalues should be negative. Namely:

$$n > p > (nk/h^2) \qquad (6)$$

In conventional magnetic bearings, k has the opposite sign, therefore, Ineq.(6) is satisfied even if $p = 0$ or without precession damper. However, in our system or conventional tops, which have unstable stiffness of tilting motion, precession damper is indispensable.

5 Precession Damper (P-damper)

Action of the P-damper is to bring tilted angular momentum vector to center axis using eddy current without bad influence to translational motion. Figure 8 shows structure of the adopted P-dampers, which consist of copper cylinders mounted on the rotor crossing horizontal flux of the stator magnets, members of the triplet magnets, as shown in Fig.2. They were set at both top and bottom parts symmetrically to avoid bad influence to translational motion, because deeply crossing parts with flux generate drag force. Nutation dampers or N-mode dampers are lumps of copper mounted on the stator sides as usual (see Fig.2).

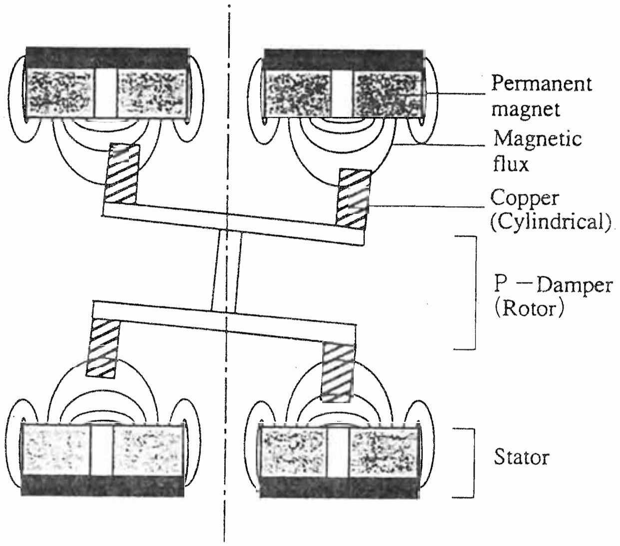


Fig.8 Damper for precession mode (P-damper)

6. Results of Experiments

6.1 Drag Test

We could rotate the rotor more than 6,000[r.p.m.] by substituting coil disc made of stacked sheets on which many thin coils were printed for molded coil disc as already described in Section 3. Perhaps, decrease of drag comes from not only thickness of the coil but also the shape which consists of two arcs and non-parallel two radial straight lines. Figure 9 shows free run test from 3,000[r.p.m.] using touch-down bearings. However, stable levitation was very difficult. Main difficulty was in low frequency translational mode. It appeared that as all coils are connected in a circle through neighboring mutual inductance, there might be some circular currents, which destabilize that mode. As will be described later, two coils out of 20 coils in Fig.7, which face each other, were cut off in order to cut the circular currents. Figure 10 shows measured drag torques of three types of coils:hexagonal molded coils, printed whole (20)

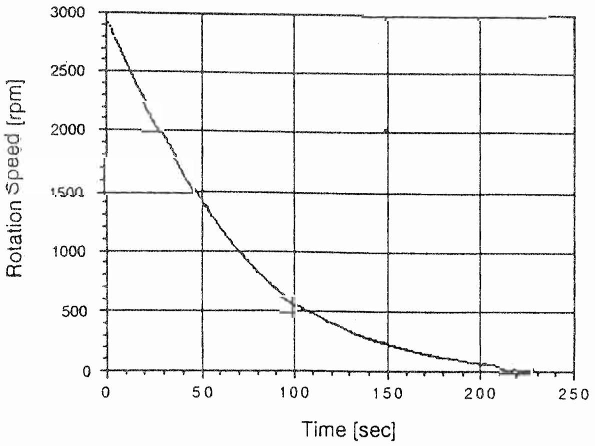


Fig.9 Free run test of null-flux coil (Total test)

coils, and printed 18 coils. Of cource, the data of the last coils shows smallest drag, which is lower than anticipated 18/20 of the whole coils. Moreover, the curve of the last one is not simple, showing that the rotor was occasionally levitated.

6.2 Levitation Test

Touch down bearings are set at outside the rotor in order to make nutation small using friction torque of the bearings, namely to make levitation easy. Gap adjustment of the triplet magnets was so burdensome task due to sensitivity of stiffnesses to the gaps that at last, weight adjuster was added to the rotor.

Though, levitation during several seconds were sometimes attained, more than ten seconds levitation seemed very difficult due to weakness of translational stability. We could not forecast this weakness of translational mode, and it seemed to us that the reason of stability weakness came from mutual inductance of neighboring null-flux coils. We cut off two coils as already stated, and succeeded in levitation of the rortor (about 7.5kg) within ± 0.5mm radial and axial air gaps of the touch-down bearings in Feb. of 1995. The rotor could be rotated up to more than 6,000r.p.m. using air turbin. After that, we stopped the air turbin and observed free motion of the rotor. Figure 11 shows Lissajou's figures of upper and lower radial displacement of wholly touched and wholly untouched or levitated spinning rotor.

More adjustments were tried: verticality of center axis of the stator, nearer approach of eddy current damper (N- damper in Fig.2) to the rotor magnets, symmetrical adjusting of upper and lower triplet magnets, and so on. As the result, from about 5,000 to 3,000 r.p.m., the rotor's untouched levitation lasted for 1min and 12sec. From 4,800 to 4,000 r.p.m., a very stable levitaion was observed as shown in Fig.12, where diameter of the lower spiral does not mean oscillation but change of magnetic center line or principal inertia axis. Outside this frequency region, during the free motion, the levitations were in not good stability, mainly translational low mode oscillations were observed, which might be attributed to mutual inductance of the null-flux coils.

6.3 Analysis of Levitaion Characteristics

Sensor output of Fig.2 were recorded and analyzed using FFT analyzers. One example is shown as Fig. 13, where rotation speed is 5,190 r.p.m. or 86.50[Hz], upper part is power spectrum of only upper x-axis (radial axis) displacement and lower part is phase difference between upper and lower x-axis displacement output which is used for discrimination of conical/cylindrical mode. In Fig. 13, many small peaks in power spectrum, and complicated shapes in the phase difference are observed.

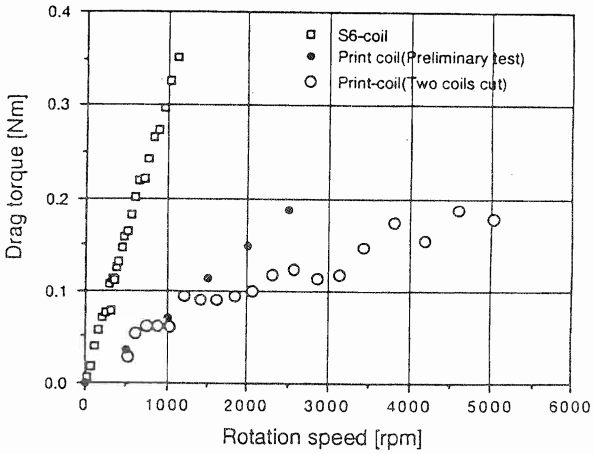
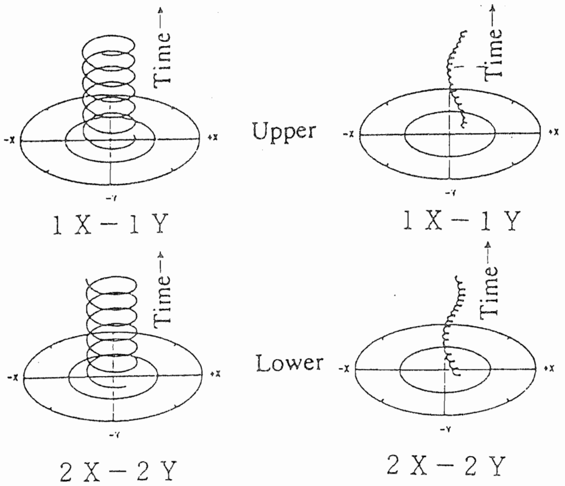


Fig.10 Data from Fig. 5 (Total test)



(a) non-levitated (N=1,800rpm)

(b) levitated (N=4,800rpm)

Fig.11 Lissajou's figure (upper and lower axis)

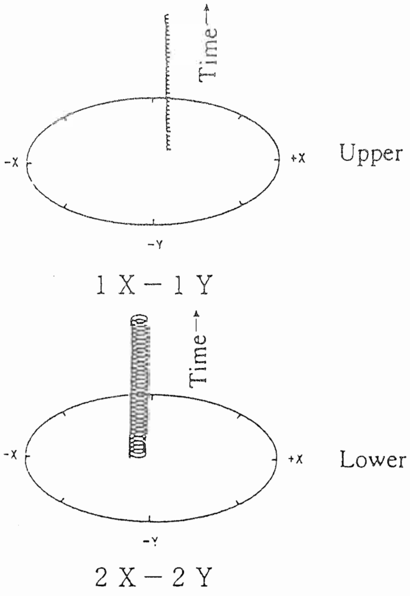


Fig.12 Lissajou's figure (levitated, N=4800[rpm])

Figure 14 shows eigenfrequencies of both conical and cylindrical modes vs rotation speed, where discrimination of the modes were based on phase differences. In Fig.14, eigenfrequency of cylindrical or translational mode f_C is about 6 Hz, then radial restoring stiffness of the total system, Krt is:

$$Krt = m(2\pi f_C)^2 = 10{,}517[N/m] \qquad (7)$$

where m is the rotor weight, 7.5[kg]. Krt consists of the stable null-flux system component Knf and unstable components Ktm by two sets of triplet magnet system:

$$Krt = Knf - Ktm \qquad (8)$$

From Eq.(8), we can obtain Knf = 11,575[N/m]. However, from the results of preliminary restoring force test using small numbers of coils, Knf = 6,000[N/m] at 5,000[r.p.m.], which is nearly one half of Eq.(7). Moreover, Krt is nearly constant in Fig.14, while the perliminary test shows increase with rotational speed. These disagreements may partly due to mutual inductance of the null-flux coils. We cut off more two coils, that is the coil disc were divided into quarters. Though power spectra changed to very simple curves, levitation became more unstable : continuous levitation without touching became almost impossible. At present, we cannot make the reason clear.

7 Problems to be Solved and Conclusion

By spinning up using air turbin, we could levitate a rotor of 7.5[kg] within radially and vertically ±0.5[mm] continuously for more than one minute without using active control and superconducting materials. Consequently, validity of principle based on sleeping tops, usefullness of triplet magnet construction and inner-rotor-type touchdown bearings were proved.

However, many problems to be solved are remained, if we want to make these results practicable. They will be enumerated as follows:

1. weakness of stiffness
2. poor stability of low frequency modes
3. disagreement of rotor axis and centerline of the stator
4. displacement of rotor axis by change of spinning speed
5. sometimes, rotor sticked to touch-down bearings
6. large influence of verticality of installation of stator to stability
7. unknown influence of mutual inductance of null-flux coil
8. sensitivity of stiffness of triplet magnet construction to gaps

and so on ··· .

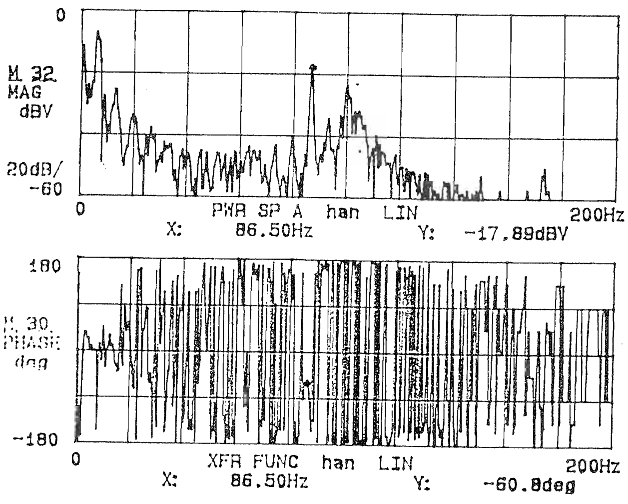


Fig.13 Power spectrum of upper displacement and phase difference between upper and lower displacement

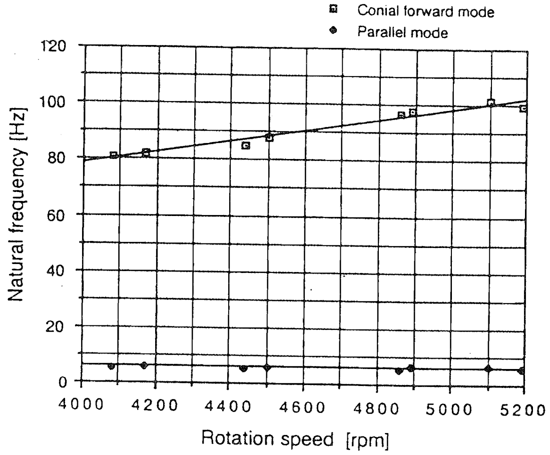


Fig.14 Two lower natural frequency in levitation

References

[1] S.Earnshaw,"On the Nature of the Molecular Forces which regulate the Constitution of the Luminiferous Ether",*Trans. Camb. Phil. Soc., 7, Part I,* pp,97-112,1842.

[2]C. Murakami, "All-Passive-Type Rotary Magnetic Bearing System Based on Stability Principle of Sleeping Tops", *JSME Intnl J. Series C,vol.38,No.3, 1995.* pp.601-608.

[3]Yonnet, J.P., "Passive Magnetic Bearing" *Proc. 3rd International Workshop on Rare-Earth Cobalt Magnets and Their Applications, (1978),* pp.241-251.

[4] Japanese Pat. pend. Dec.1991, No.3-330557.

[5] Japanese Pat. pend. Feb.1993, No.5-56561.