2nd International Symposium on Magnetic Beaing
July 12-14, 1990, Tokyo, Japan

IRON LOSSES AND WINDY LOSSES OF HIGH ROTATIONAL SPEED ROTOR SUSPENDED BY MAGNETIC BEARINGS

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Abstract

The power losses of a rotor suspended by magnetic bearings are lower than that by conventional ball bearings, slide bearings and so on. This merit comes from no mechanical contact which is unique characteristic of magnetic bearings. The power losses of magnetic bearings consist of iron losses (the sum total of eddy current losses and hysterisis losses) and windy losses (due to the friction between the rotor surface and the air). In the high rotational speed region, the power losses tend to increase and must be considered when we design the rotor system. We can easily estimate the sum total of power losses by the free deceleration characteristics of the rotor and separate between iron losses and windy ones by the comparison between the results in the vacuum and in the air.

In this paper, we try to derive the equation of iron losses based on the results of deceleration experiment for some softferromagnetic materials (2 different thickness of silicon steel, amorphous alloy and so on) and for several steady state currents in the vacuum (1×10^{-3} torr). As to windy losses, on the other hand, we try to compare the experimental results with the theoretical ones from the view point of hydrodynamics.

1. Introduction

Recently, magnetic bearing systems are under investigation about applications for industrial machines, i. e., internal grinding spindle, milling spindle, etc. These small, high rotating rotors must be designed to have large diameters and short length to set its 1st resonant bending mode frequencies high enough to nominal rotational speeds. But some problems written below will follow.

1) Burst or destruction of the parts; motor rotor, armature of magnetic bearings.
2) Shortage of output power of motor reduced by rotational power losses.

To overcome these problems,

A) Spinning burst test of the parts made of especially soft ferromagnetic materials.
B) Development of excellent performance motor; high peripheral speed, high power.
C) Grasp of the power losses in the state of highspeed rotation of magnetically suspended rotor and feed back to rotor design.

are necessary.

In this paper, dealing with term C), characteristics of iron losses of several ferromagnetic materials and of windy losses of several rotors are reported.

2. Experimental equipment

Each spindle we experimented is suspended by 5-axis active controlled, D.C.-type magnetic bearings. The experimental equipment (Fig. 1) and pole arrangement of radial magnetic bearings (Fig.2) are shown. In these experiments, the spindles are set perpendicularly only.

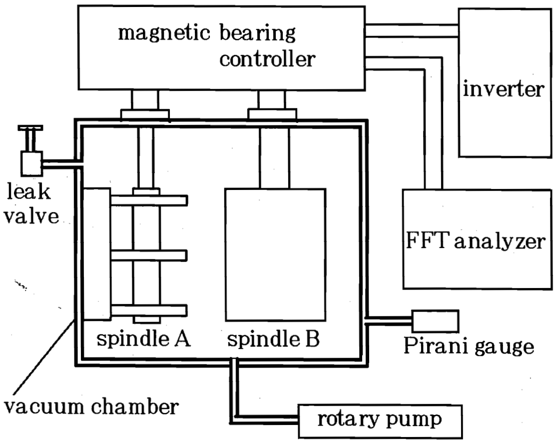


Fig. 1 experimental equipment

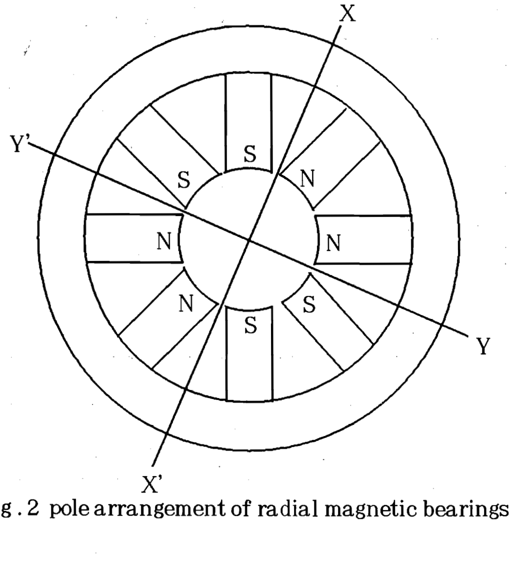


Fig. 2 pole arrangement of radial magnetic bearings

The values of rotational losses are calculated from the characteristics of free deceleration of rotor by the following manner.

Accelerating the rotor to nominal rotational speed by highfrequency induction motor built in the spindle, we cut off the input power of the motor, and the rotational speed is measured by FFT by means of processing the signal of displacement sensor that the magnetic bearings itself have, while the rotor is decelerating without any load. The power losses are obtained by the following equation.

$$W_{(N)} = 1/\Delta T/2 \cdot I_Z \cdot (N1^2 - N2^2) \cdot (\pi/30)^2 \text{———} (1)$$

N : rotational speed $N_{(rpm)} = (N1 + N2)/2$
ΔT : deceleration interval of N1 to N2
Iz : polar inertial moment of rotor around rotational axis

When the iron losses W_I for several Io (steady state currents) of radial magnetic bearings are measured, the pressure in the chamber is reduced below 1×10^{-3} torr by rotary pump to be uneffected by hydraulic friction. So the windy losses $W_{W(N)}$ can be estimated by the next equation.

$$W_{W(N)} = W_{(N,Io)} - W_{I(N,Io)} \text{——————} (2)$$

Although W_I was measured for several steady state currents of axial magnetic bearing, any dependence on the currents was not found in the deceleration characteristics. So the iron loss of axial magnetic bearing is recongnized little enough to be ignored.

3 . Materials for rotor armature of magnetic bearings

Table.1 shows the materials of rotor armature of radial magnetic bearings experimented for W_I and their characteristics.

Table . 2

No.	material	thickness (mm)	tensile strength (kg/mm²)	resistance (μΩ-cm)	insulator
1	silicon steel	0.35	53	49	inorganic
2	↑	0.10	49	52	↑
3	amorphous (Fe)	0.03	>200	130	———
4	maraging steel	0.05	185	52	oxide

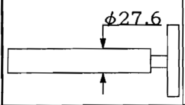
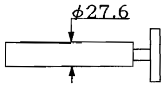
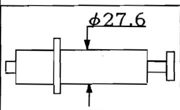
Amorphous alloy is ordinarily used for core of high frequency transformer after magnetic annealing. This heat treatment will better its magnetic characteristics, especially permability. But its mechanical characteristics, especially toughness, will be impaired. It is not practical for shrink fitting to use annealled amorphous alloy. So the rotor of amorphous alloy was used and laminated without the heat treatment and insulation too.

On the other hand, maraging steel has high tensile strength and toughness and is used for the rotor of centrifuge. It is easy to suppose that this material brings about huge hysterisis losses, because it is half hard feromagnetic material. To obtain higher rotational performance, this test was attempted.

4.Rotors

All of the rotors experimented are 3 types with the same rotor diameter at radial magnetic bearings. The shapes of the rotors and combinations with armature materials are shown in Table.2.

Table . 2

No.	shapes	material	Iz	housing
A		1	1127 (gr-cm²)	block type
B		1 2	888 (gr-cm²)	enclosed type
C		1 2 3 4	625 (gr-cm²)	enclosed type

5 .Iron losses

Iron losses (W_I) can be measured directly by the deceleration characteristic in the vacuum. The experimental results of W_I are shown in Fig.3 − 6.

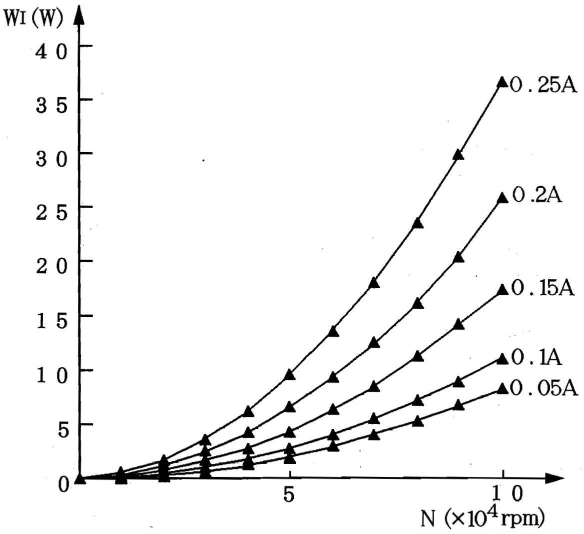


Fig.3 W_I of Silicon steel (t = 0 . 35)

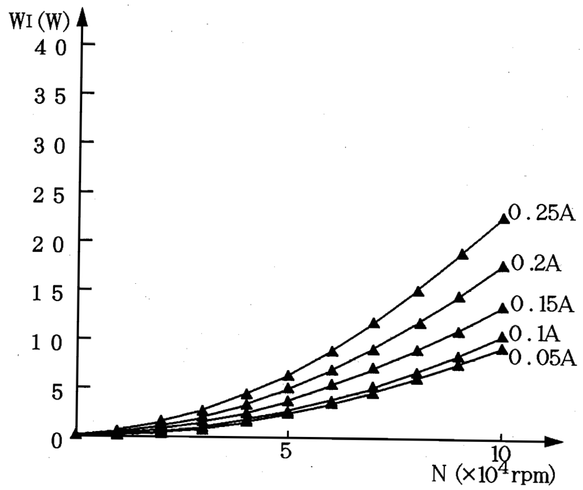


Fig . 4 W_I of Silicon steel (t = 0 . 1)

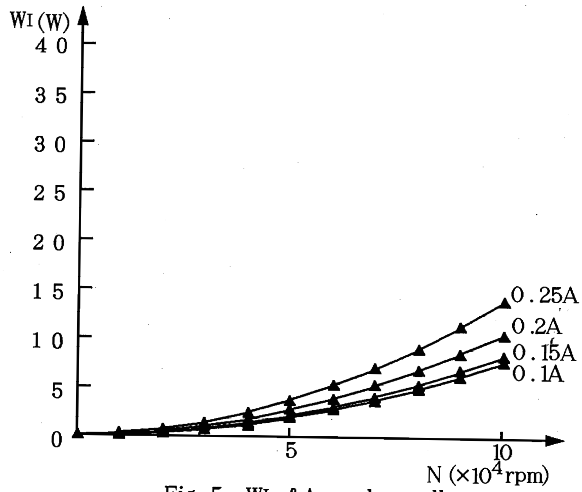


Fig . 5 W_I of Amorphous alloy

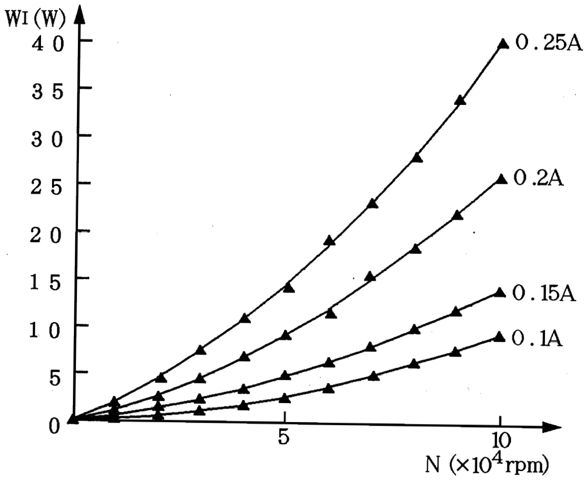


Fig . 6 W_I of Maraging steel

Generally speaking, iron losses can be given of the sum total of hysterisis losses (W_h) and eddy current losses(W_e). The former is in proportional to frequency (f),and the latter is in proportional to f^2. So we assume that W_I can be presented by the following equation.

$$\begin{aligned} W_I &= W_h + W_e \\ &= H\cdot N + E\cdot N^2 \quad \text{———} \quad (3) \end{aligned}$$

H : hysterisis coefficient
E : eddy current coefficient

The coefficient H and E, can be obtained for each steady state current Io from Fig.3−6 are drawn in Fig.7,8.

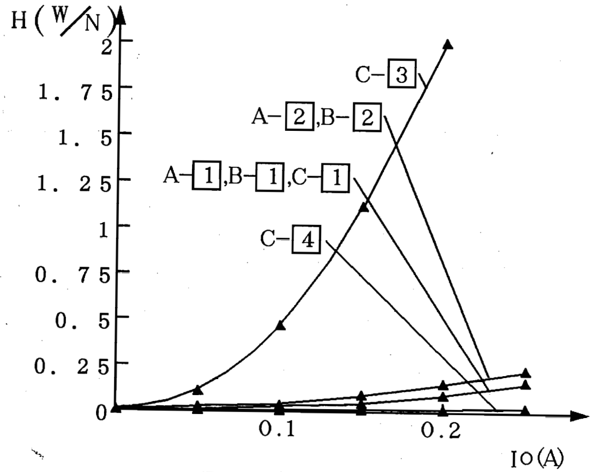


Fig . 7 hysterisis coeffcient

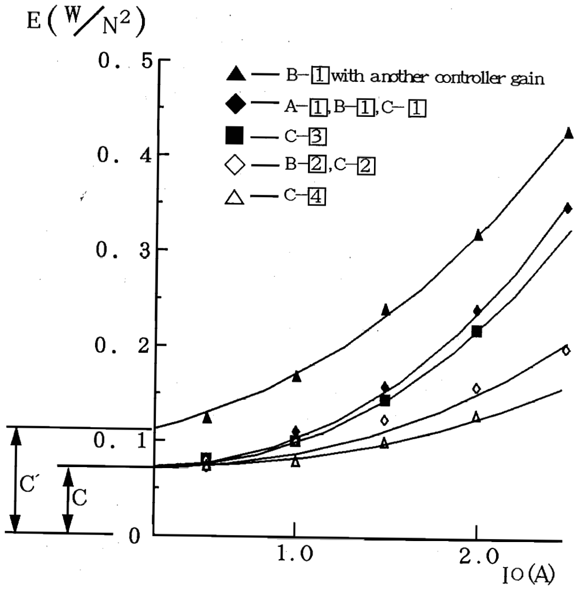


Fig . 8 eddy current coefficient

Judging from these diagrams, it can be said that H and E are in proportional to Io^2 , however E includes offset term C. Synthesizing these results, the following experimental equation is obtained.

$$W_I = h \cdot Io^2 N + (e \cdot Io^2 + C) \cdot N^2 \text{ ——— } (4)$$

Table. 3 shows h and e for each material. Being expected before, the high value of h for $\boxed{4}$ shows huge W_h. On the other hand, it is noticeable that h and e for $\boxed{3}$ are about 1/3 for conventional $\boxed{1}$.

Table. 3

material No.	h(W/N·A²)	e(W/N²·A²)
$\boxed{1}$	2.5	4.0
$\boxed{2}$	3.8	2.3
$\boxed{3}$	0.8	1.5
$\boxed{4}$	51.0	3.8

Offset C has a certain relation to control gain, because in case of higher control gain of radial bearings is set, offset C increase to C'. C maybe depend on control current Δ I. However, we can't recongnize such offset for H. The reason of it can be supposed that the control current Δ I for stabilizing the rotor has little effect on H, because it only increases the hysterisis of the minor loop. But Δ I usually includes higher frequency components, so it may has much contribution on W_e.

By the way, the values of H and E for the case of A-$\boxed{1}$ (A spindle and $\boxed{1}$- rotor), B-$\boxed{1}$ and C-$\boxed{1}$ are nearly equal unintentionally, also B-$\boxed{2}$ and C-$\boxed{2}$ too. It is quite natural for A and B, because they have same radial magnetic bearings. Examining into the reason, we found that the following relation happened to be formed for B spindle and C spindle.

$$L_A N_A^2 = L_B N_B^2 \fallingdotseq L_C N_C^2 \text{ ——— } (5)$$

L_I : total lamination width of radial magnetic bearings
N_I : number of winding turns for each radial magnet
I : shows I spindle

Eq.(5) means that the steady state attractive force F_O of each spindle coincides, because...

$$F_O \propto S \cdot B_g^2 \propto (D_i \cdot L_i) N_i^2 \cdot I_O^2 \text{ ——— } (6)$$

S : attractive area
Di : diameter of radial magnetic bearings
Bg : magnetic flux density at the air gap

In short, for the same armature material, the coefficient H and E are in proportional to F_O.

hence

$$W_I = \overline{h} \cdot F_O \cdot N + (\overline{e} \cdot F_O + C) \cdot N^2 \text{ ——— } (7)$$

Furthermore,

$$W_I = \overline{h} \cdot \Sigma F \cdot N + (\overline{e} \cdot \Sigma F + C) \cdot N^2 \text{ ——— } (8)$$

here,

$$\Sigma F = \sum_j \sum_k F_{jk} \text{ ——— } (9)$$

j = X , Y
k = 1 , 1´, 2 , 2´

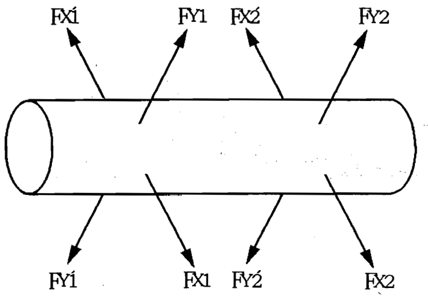


Fig . 9 configuration of magnetic forces

6. Windy losses

Windy losses can be estimated by subtracting W_I from W; total rotational losses obtained from deceleration characteristics in the air.

$$W_W = W - W_I = W(I_O) - W_I(I_O) \text{ ——— } (10)$$

The windy losses of B spindle for several Io are shown in Fig. 11. The values of windy losses, naturally independent of Io, coincide with each other, meaning that the measurement and the separation has enough precision.

Now, the rotational friction losses of cyliynder or disc in the infinite vessel can be described by useing Karman's coefficient of the resisting moment C_f.[3]

for cylinder

$$W_{W_1} = \pi\rho/g \times \omega^2 \times (D/2)^4 \times l \times C_{f1} \times 1.027 \times N \text{ — } (11)$$

for disc

$$W_{W_2} = \rho/2g \times \omega^2 \times (D/2)^5 \times C_{f2} \times 1.027 \times N \text{ ——— } (12)$$

here

$C_{f1} = 1.728 \times R_{e1}^{-0.5}$ (for laminar flow)
$\qquad 0.072 \times R_{e1}^{-0.2}$ (for turbulent flow)

$C_{f2} = 1.935 \times R_{e2}^{-0.5}$ (for laminar flow)
$\qquad 0.072 \times R_{e2}^{-0.2}$ (for turbulent flow)

$R_{e1} = 2\pi r_1^2 \omega/\nu$
; peripheral Reynolds number for cylinder
$R_{e2} = r_2^2 \omega/\nu$
; peripheral Reynolds number for disc
r_1 ; radius of cylinder
r_2 ; radius of disc
$\nu = 1.501 \times 10^{-5} (m^2/s)$
; coefficient of kinetic viscosity of the air

ω ; angular velocity of cylinder or disc
$\rho = 1.2(\mathrm{kg}/\mathrm{m}^3)$; density of the air at 20℃
$g = 9.8(\mathrm{m}/\mathrm{sec}^2)$; gravitational acceleration
$N = \omega\cdot(30/\pi)$; rotational speed in rpm

Substituting the constants and coefficients into eq. (11), (12) and rearranging, the following equation for the total windy losses can be obtained.

$$Ww \doteqdot (4.43\times10^{-8}\times\Sigma D_1^3 l+1.006\times10^{-8}\times\Sigma D_2^4)N^{2.5}(\mathrm{w})$$
$$\text{(for laminar flow)} \text{ —— } (13)$$

D1 ; diameter of cylinder (mm)
l ; length of cylinder (mm)
D2 ; diameter of disc (mm)
N ; rotational speed ($\times10^4$rpm)

The first term of eq. (13) describes Ww for the cylinder part of rotor, and the second term for the disc part.
Rec(critical Reynolds number) at which transition to turbulent flow occurs is about 5×10^5. For the region above Rec, eq.(13) must be changed into the following equation.

$$\begin{aligned} Ww \doteqdot\ & (4.435\times10^{-8}\times\Sigma D_1^3 l+1.006\times10^{-8}\times\Sigma D_2^4)N^{2.5} \\ & \text{(for laminar flow)} \\ & + \\ & (7.89\times10^{-8}\times\Sigma D_1^{3.6} l+8.849\times10^{-10}\times\Sigma D_2^{4.6})N^{2.8} \\ & \text{(for turbulent flow)} \end{aligned} \text{ ——— } (14)$$

Calculated results from eq. (13) and (14) are compared with the experimental ones in Fig.11. Eq. (13) is correct only in the region $N < 20000$ rpm. Eq. (14) is also correct in the region $N < 60000$ rpm. Furthermore, considering the clearance between rotor and surrounding electro-magnets that have smooth inner surface molded by epoxy regin, not in the infinite vessel, the flow can be thought as Couette flow. [4]
With the assumption that Couette flow may occur, the coefficient of the resisting moment becomes

$$\begin{aligned} C_f &= 0.00759\ R_\omega^{-0.24} \\ &= 0.00759\ (r_m\cdot\delta\cdot\omega/\nu)^{-0.24} \end{aligned} \text{ ——— } (15)$$

$r_m = (r_i + r_o)/2$
$\delta = (r_i - r_o)$; gap
r_i ; inner radius of electro-magnet
r_o ; outer radius of rotor

and

$$\begin{aligned} Ww \doteqdot\ & (4.435\times10^{-8}\times\Sigma D_1^3 l+1.006\times10^{-8}\times\Sigma D_2^4)N^{2.5} \\ & \text{(for laminar flow)} \\ & + \\ & (7.89\times10^{-8}\times\Sigma D_1^{3.6} l+8.849\times10^{-10}\times\Sigma D_2^{4.6})N^{2.8} \\ & \text{(for turbulent flow)} \\ & + \\ & 1.2893\times10^{-9}\,\Sigma D_1^{3.76} l\cdot N^{2.76} \\ & \text{(for Couette flow at cylinder)} \end{aligned} \text{ ——— } (16)$$

The estimated values by eq. (16) explain the experimental results very well.
In the case of A spindle, because the housing is separated block type, the windy losses tend to fit the turbulent flow, as shown in Fig.10.

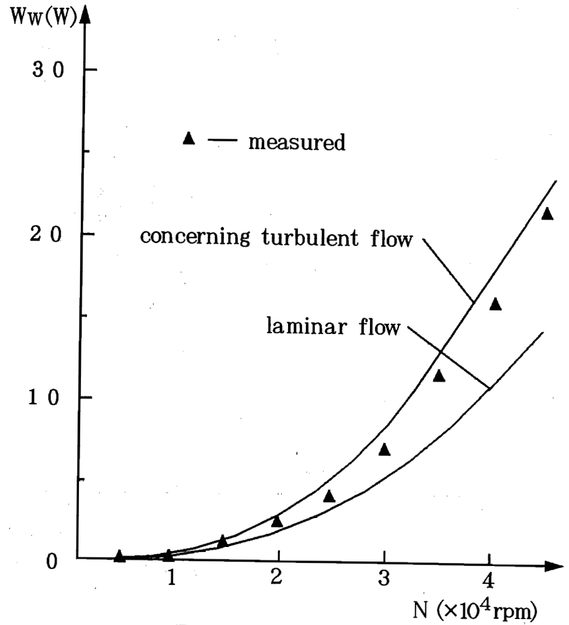


Fig. 10 Ww of spindle A

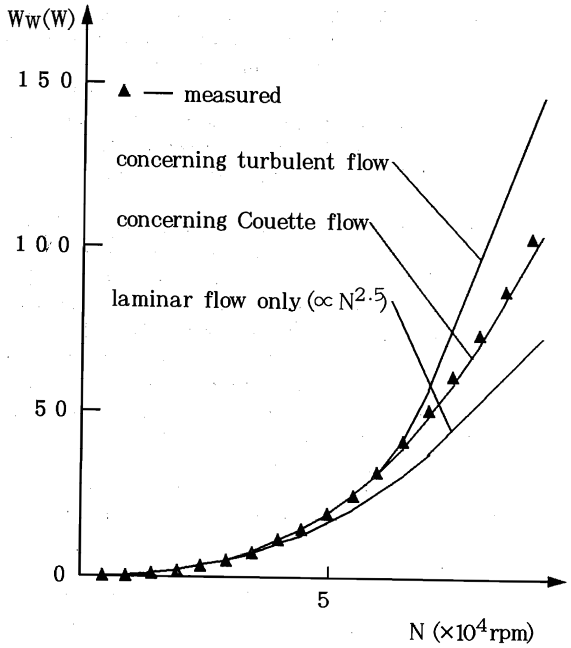


Fig. 11 Ww of spindle B

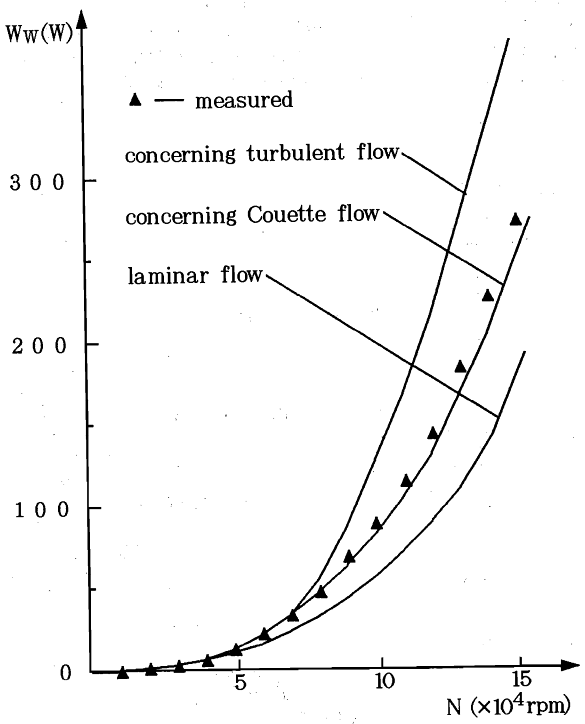


Fig. 12 Ww of spindle C

7.Summary

Following aspect about iron losses and windy losses of high rotational speed rotor suspended by magnetic bearings is obtained.

1. With the assumption of experimental eq. (3) about W_I, eq. (4) that has control-term C in the term being in proportional to N .
2. The values of coefficient h and e^2 that have relation to hysterisis losses and eddy current losses respectively, being included by eq.(4) are decided experimentally.

Furthermore,

3. Eq.(8), more genelarized form, is offered.
4. About windy losses, the comparison with theoretical value, from the view point of hydrodynamics, of laminar or turbulent flow and experimental value is achieved.
5. It is shown that, for the cylinder part of rotor having little clearance to housing, the experimental value is precisely explained with the assumption of Couette flow.

We express our thanks to AICHI STEEL CO,.LTD. for offering maraging steel and its technical supports.

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