Vibration	Backward Whirling of Vertical Rotating Shaft	Rotating
Nonlinear	Supported by Bearing with Backlash	Machinery

Object Machine

Testing apparatus having a vertical rotating shaft (Fig.1), Variable speed motor (40W, 0 ~ 5,000rpm), Vertical rotating shaft (made of steel, diameter D = 12mm, span l = 800mm)
　　Top part: self-aligning ball bearing
　　Bottom part: sliding bearing without lubrication oil (made of brass, diametrical gap C_d = 1 ~ 1.5mm)

Observed Phenomena

If a suitable external disturbance was applied to the vertical shaft rotating at a constant speed of 100 ~ 1,000rpm, the rotating shaft experienced a relatively high speed backward whirling after colliding with the bottom part bearing having backlash. The backward whirling has two patterns (Fig.2 (a), (b)). In the case of one of them, the rotating shaft rolls in the backward direction on the bearing inner circumference surface without slip. In this case, trajectory of the shaft center is smooth, with an angular velocity of whirling $\Omega = (D/C_d)\omega$, ω: rotational speed (Fig.3). In case of the other one, the rotating shaft whirls in the backward direction with the primary or the secondary bending natural frequency ω_n of the shaft without bearing backlash. This whirling occurs in the rotational speed range to satisfy $\omega_n \approx (D/C_d)\omega$, (Fig.3), and the shaft whirls while touching or detaching the bearing inner circumference. Compared with the first case, the friction torque remarkably increases in the second case of backward whirling (Fig.4).

Cause Estimation

The cause of generation of backward whirling is considered to be a dry frictional force between the shaft and the bottom bearing face. If the friction torque is larger than the driving torque, a backward whirling pattern is generated where the former rotates without slip. However, if the backward whirling speed comes close to the bending natural frequency ω_n of the shaft without backlash, the vibration of eigenmode remarkably occurs. Even if the driving torque is increased to raise the rotational speed under such a condition, the backward whirling speed remains ω_n. As a consequence, slip occurs under the latter whirling pattern (actually, repetition of touching and detaching).

Analysis and Data Processing

The friction torque upon occurrence of backward whirling is calculated as in the following. Deflections at several points of the shaft during backward whirling were measured (Fig.5 (a), (b)). The moment of centrifugal force due to deflection around the top bearing O is obtained, which is equalized with the moment around the vertical load N of the bottom bearing O.

$$Nl = \int_0^l \rho A \omega^2 r(z) z \, dz$$

z : Vertical axis (distance from top bearing O)
$r(z)$: Radial displacement in Fig.5
l : Distance from top bearing O to bottom bearing (=800mm)

Frictional torque T_q is　$T_q = \mu N \frac{D}{2}$　　　($\mu = 0.3$)

The results obtained are shown with ● in Fig.4 (C_d = 1cm).

Countermeasures and Results

(1) Backward whirling has two patterns as mentioned above.
(2) The frictional torque upon occurrence of backward whirling can be roughly obtained by the centrifugal force due to deflection of the rotating shaft.

Lesson

(1) Even for a low rotational speed ω, the backward whirling speed $(D/C_d)\omega$, that is fairly high, thus attention must be paid.
(2) If the backward whirling speed becomes equal to the natural frequency of bending of the system without backlash, frictional torque remarkably increases, thus attention must be paid.

References

Sawaragi G, Iwamoto Y, "Shaft whipping induced by a dry friction of bearing", (in Japanese) Transactions of the JSME, Vol.17, No.57 (1951), pp.61-66
Black H.F, "Interaction of a whirling rotor with a vibrating stator across a clearance annulus", J. Mechanical Engineering Science, Vol. 10, No.1 (1968), pp.1-12.

Keywords

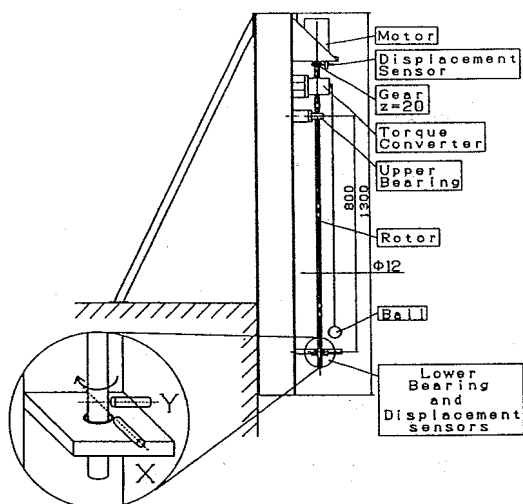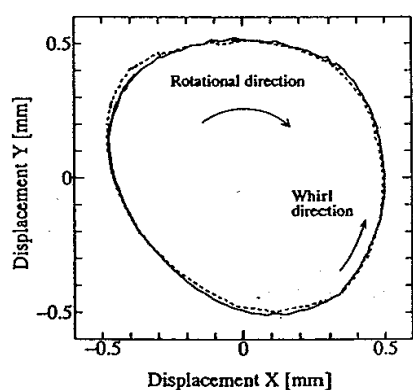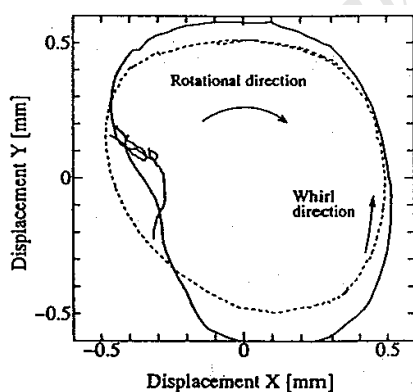Backlash, backward whirling, frictional force, rotating shaft

Fig.1 Experimental apparatus

(a) Non-slip type

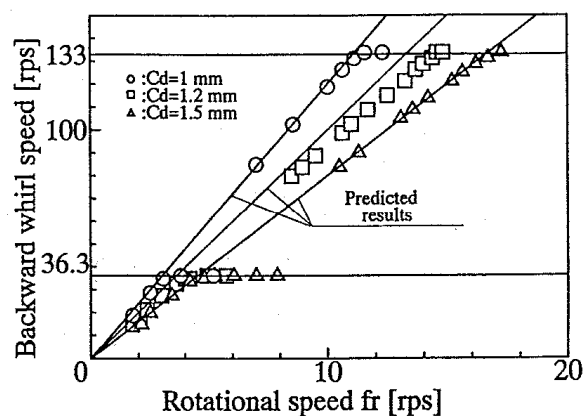

(b) Eigenmode type

Fig.2 Trajectory of backward whirling

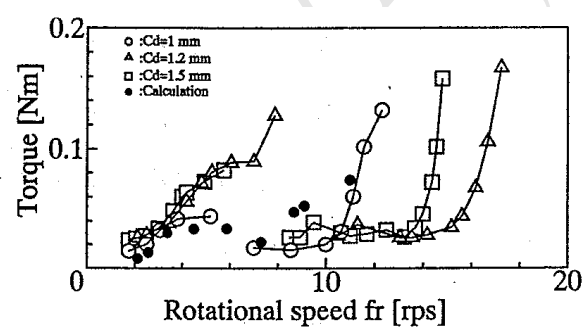Fig.3 Changes in backward whirling speed for rotational speed

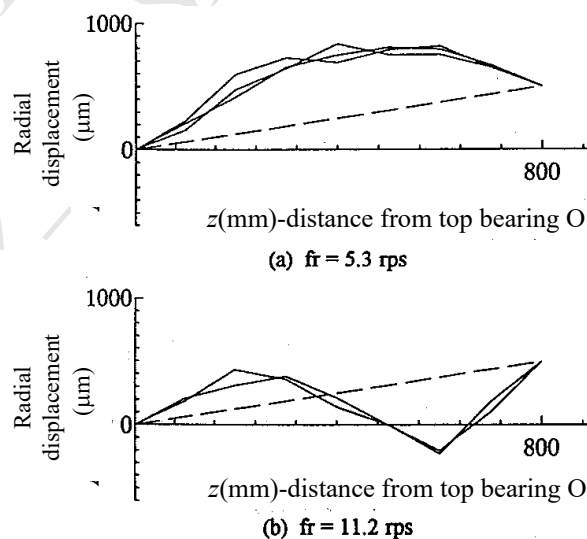Fig.4 Frictional torque due to backward whirling

(a) fr = 5.3 rps

(b) fr = 11.2 rps

Fig.5 Shaft deflection during backward whirling