Case History	Unstable Vibration of Rotor Containing Liquid
Self-excited Vibration	

Object Machine

Experimental centrifuge (rotating body with a cylindrical container including liquid at the overhang position of the shaft)

Observed Phenomena

When water was being poured into a rotating hollow cylinder, violent whirling vibration occurred, which was characterized by the facts that: (1) the frequency of whirl was proportional to the rotational speed in asynchronous mode, (2) the said frequency was changed to a lower frequency side for increasing water depth, and (3) the violent vibration occurred in an area close to the natural frequency of the shaft or the frame.

Cause Presumed

A rotating body containing liquid has a natural frequency of oscillation of the inside liquid. It was considered that, at an area where the difference between the natural frequency of liquid oscillation and the rotational speed almost coincided with the natural frequency of the rotating body, both the inside liquid and the rotating shaft resonated, resulting in enhancement of violent rotor vibration in a self-excited mode.

Analysis and Data Processing

Three types of experimental models were prepared that represented rotating hollow containers with different sizes (Table 1, Fig.1), which were used for frequency analysis of the waveforms of whirling vibration of the rotating shaft. At the same time, pressure waveforms caused by oscillation of the internal liquid were analyzed using an ultracompact pressure sensor and an FM telemeter, together with an analysis of the correlation with rotor vibration. In addition, oscillation of the liquid surface during rotation was observed using a CCD camera.

By applying a simplified sloshing equation, the natural frequency of liquid surface oscillation and oscillation mode under the influence of centrifugal force field were obtained (Fig.2). Depending on the combinations of circumference and axial direction mode, innumerable liquid surface oscillations are conceivable. Analysis of the internal pressure mode on the basis of pressure measurements (2, 1) revealed a mode shifting to the circumference direction. Plotting the relationship between the rotor vibration and the predominant frequency of pressure fluctuations provided a good agreement with the results obtained in Equations (1) and (2), and thus verified that the difference between the shaft rotating frequency and the liquid surface oscillation frequency was equal to the frequency of the observed shaft whirl. It was further clarified that the frequency area for the violent vibration to develop was an area where the rotating shaft natural frequency and the internal liquid oscillation frequency agreed (Figs.3, 4, 5 and 6).

Moreover, whirling vibrations were compared by changing the number of vertical partition plates (circumferentially arranged). When two vertical partition plates were used, the inside liquid was completely eccentric, showing rotation synchronous unbalance. With no plate, or with three, four, five and six partition plates, vibration due to oscillation of the inside liquid occurred, while for the number of plates of three or less and four or more, the condition for occurrence of vibrations was different. That is, vibrations in case of four or more plates are the same as those to occur due to the above reason, and the property of vibrations apparently remains unchanged when the number of partition plates is changed.

Countermeasures and Results

The frequency of liquid oscillation was raised to avoid resonance by installing inside the container several circumferential partition plates of such a shape as not to exert influence on the separation performance.

Lesson Learned

Although problems of this type have long been treated in many studies, it seems that problems dealing with axial oscillation as taken up in this Case are rather rare. Particularly, in the case where amplitudes on both sides of rotor axial direction are different, liquid oscillation may be excited depending on the combination of axial direction and circumferential direction, which requires consideration to be given. Also attention should be paid as this sort of vibration is extremely violent and difficult to be treated.

References

(1) Ide, K.; Kazao, Y.; Watanabe, S. Proceedings of Dynamics and Design Conference, No.910-99 (3B) (1991), 224
(2) Ide, K.; Kazao, Y.; Watanabe, S.; Yabu, T.; Sakai, T. Proceedings of Dynamics and Design Conference, No.940-26 (IA) (1994), 342
(3) Morishita; Yamamoto. Proceedings of Dynamics and Design Conference, No.940-26 (IA) (1994), 338
(4) Ide, K.; Kazao, Y.; Watanabe, S.; Yabu, T.; Sakai, T. ASME, DE-Vol.84-3, '95 D.E.T, Vol3-C, 1347-1355

Keyword

Unstable vibration, rotor containing liquid, sloshing

The Japan Society of Mechanical Engineers (No.96-5 II) "Examples of Mechanical Vibrations for Designers" "v-BASE" forum materials (August 6, 1996 in Fukuoka City)

Table 1: Dimensions and natural frequency of experimental apparatus

Model Case		A	B	C
Rotor shape φ	D (mm)	400	900	170
	L (mm)	260	500	150
Sensor position	La (mm)	157	1680	192
Rotor position	Lb (mm)	689	1540	357
Stopper position	Lc (mm)	314	1700	225
Gap	б (mm)	1.0	10.0	2.5
No. of axial partitions	P	8	4	5
- Natural frequency in pendulum mode (Hz)		9.75	4.9	9.7

- When hollow cylindrical rotor is not in rotation and with no liquid in it.

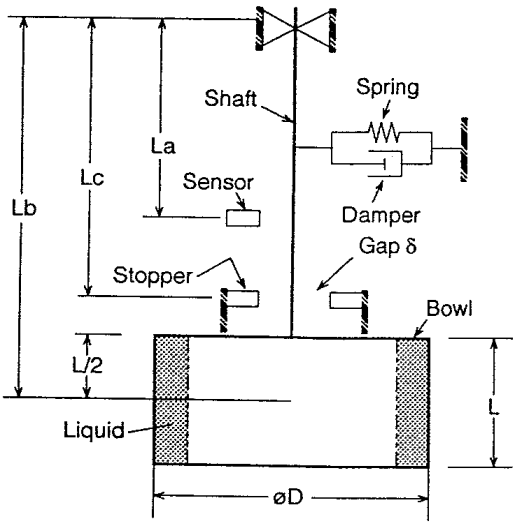

Fig.1: Shape of experimental apparatus

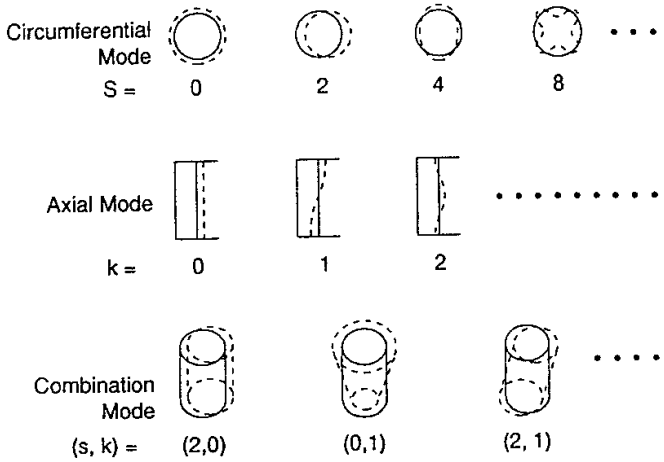

Fig.2: Oscillation mode of inside liquid

Centrifugal acceleration acting on the liquid is substituted to the term of gravitational acceleration in the equation of generalized sloshing frequency, and an approximate expression (1) is obtained for the sloshing frequency of liquid inside a rotating container.

$$\omega(s,k) = \sqrt{\frac{r\Omega^2}{L}\left[\pi\sqrt{s^2+\left(\frac{kL}{b}\right)^2}\times \tanh\left[\left(\frac{\pi h}{L}\right)\sqrt{s^2+\left(\frac{kL}{b}\right)^2}\right]\right]} \quad \text{..... (1)}$$

Here,
Ω: rotation angular velocity
rΩ2: typical centrifugal acceleration
ω (s,k): sloshing natural angular frequency of (s,k) mode
r: typical radius (intermediate position along liquid depth r = a - h/2)
a: external diameter of liquid inside cylinder
h: liquid depth
L: typical circumferential length (L = 2πr)
b: circumferential length
s: mode order in circumferential direction; s = 0, 2, 4, 6 (from symmetry)
k: mode order axial direction; k = 0, 1, 2, 3……

Figure 2 shows oscillation waveforms of the liquid free surface for the mode order (s,k).
If sloshing ω (s,k) occurs in a rotating container, the rotating body that is subjected to this liquid force whirling-rotates with a frequency fR. When viewed from the stationary side, the frequency fR of rotor

vibration for rotational speed N is given by:
$f_R = N - \omega(s,k)/2\pi$ … (2)

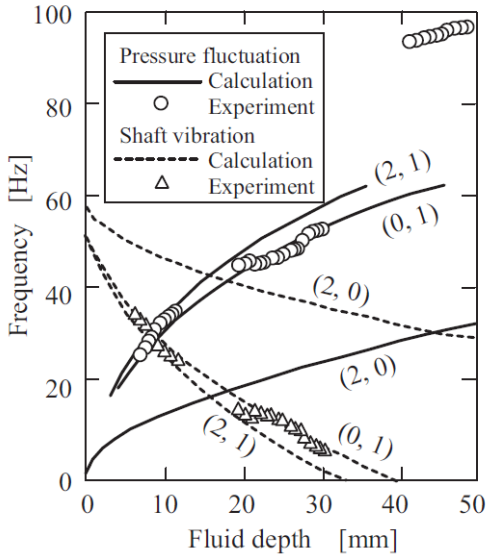

Fig.3: Relationship between liquid depth and vibration frequency (Model A, rotational speed N = 60 Hz)

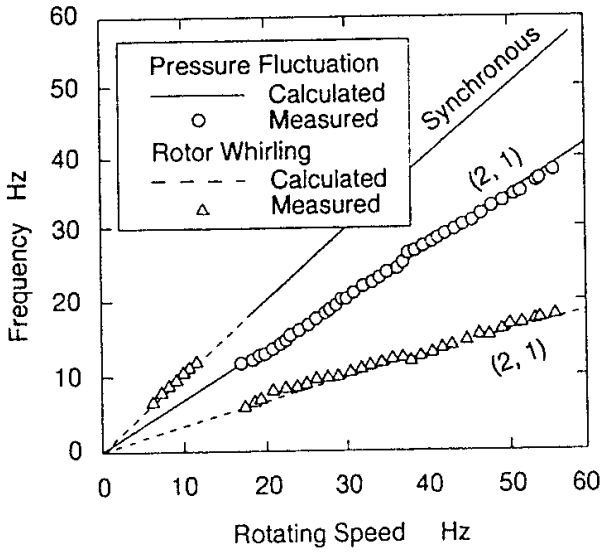

Fig.4: Relationship between rotational speed and vibration frequency (Model A, liquid depth h = 15 mm)

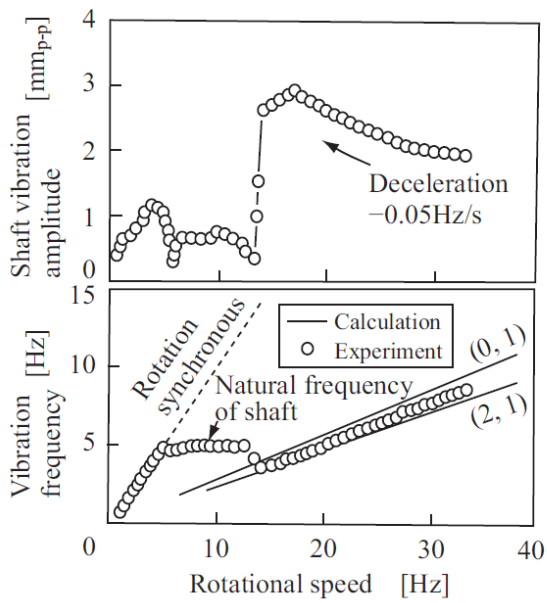

Fig.5: Relationship between rotational speed and rotor vibration (Model B, liquid depth h = 30 mm)

Frequencies showing maximum amplitude on the frequency analysis diagram were plotted.

a: Natural frequency component
b: Rotating synchronous component
c: Component induced by the fluctuaiton of the liquid in the rotor.

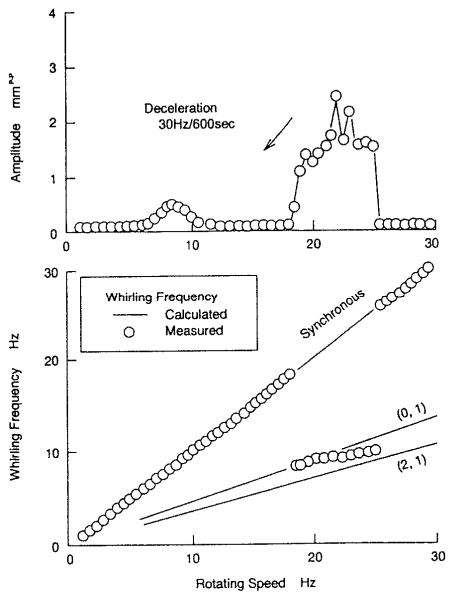

Fig.6: Relationship between rotational speed and rotor vibration (Model B, liquid depth h = 9 mm)

Frequencies showing maximum amplitude on the frequency analysis diagram were plotted.

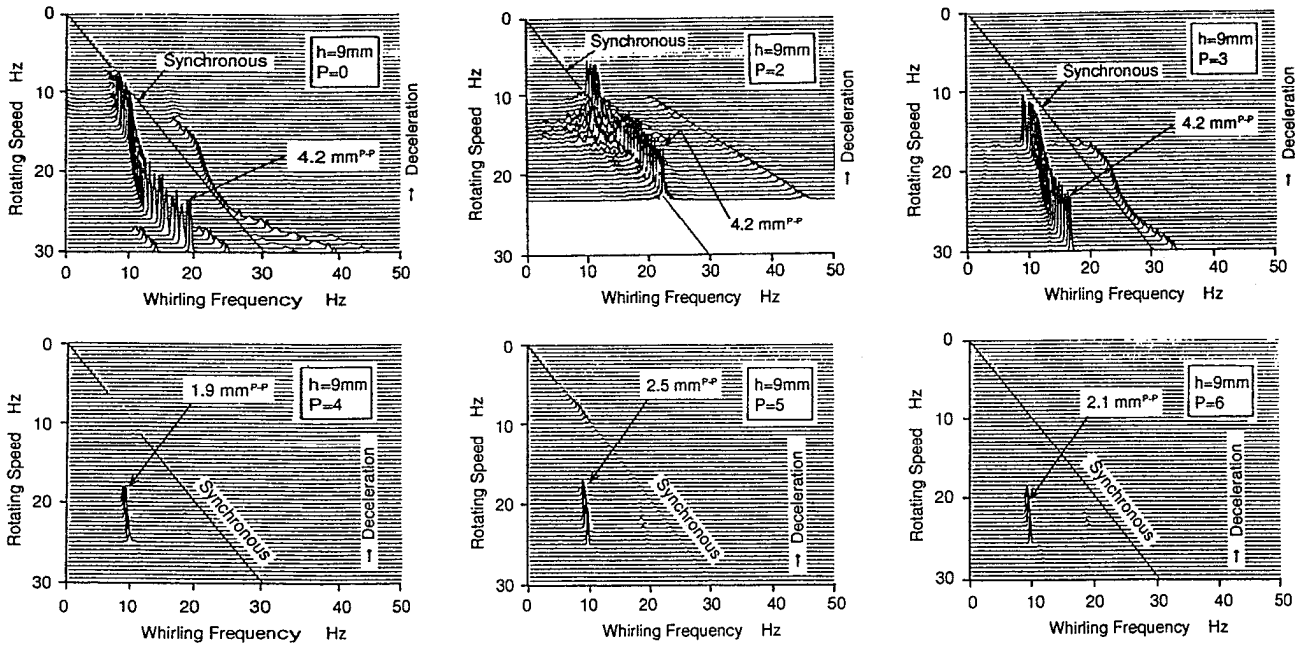

Fig.7: Influence of the number of vertical partition plates (axial direction)

(Model C, liquid depth h = 9 mm, for the number of partition plates P = 0, 2, 3, 4, 5, 6)