

NONLINEAR VIBRATION OF A MOVING BODY CAUSED BY FRICTION

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Abstract: The nonlinear phenomenon of the vibration of a rotating machine is studied experimentally and numerically. The rotating part of the machine has a contact surface with static elastic surface. Vibration of the rotating part itself without any contact to the surface is considered as linear problem. Inviting frictions on the contact surface causes nonlinear phenomena, which cannot be explained by linear concepts, such as multiple attractors, chaotic orbits and bifurcation behavior.

The experiment is focussed the influence of the friction on the behavior of the rotating part. With the help of the mathematical analysis, the mechanism of the influence is understood. The result obtained offer an engineering solution using nonlinear concept.

Keywords: Friction, Vibration, Rotating Machine

1 INTRODUCTION

Friction is a common problem met in engineering whenever there is relative movement between mechanical parts. Lubricant is used in rotating machines to reduce the friction, but in many cases friction induced vibration cannot be avoided. Generally, the friction-induced vibration is of broadband. However the structure behavior depends on its frequency character. A rotor-bearing system is such designed that its critical speeds are carefully chosen so that severe resonance of the structure can be avoided. For some high speed rotating machines, which work in supercritical state, the sport system of the rotor is very flexible. This kind of machines is sensible to friction. Mottershead [1] has given a thorough description of the friction-induced instability in disks, which was focused on mathematical analysis. Here we report an experimental study of a rotating body with friction in its bearing and give the way to an engineering application solution.

2 FRICTION PHENOMENON IN A ROTATING MACHINE

A prototype of flywheel is being developed. The assembly consists of a rotor of 1 kg, an up magnet bearing which unloads 80% of the rotor's weight, a down mechanical bearing with lubricant and a damper. The mechanical bearing is the only part having mechanical contact. This rotor-bearing system is a multibody system. There are 5 natural frequencies between 0-6.5 Hz. Mostly, this machine works well in short term. The design is aimed at long term operation, say more than 10 years, so it is important to ensure that the mechanical bearing being lubricated well all the time.

In operation experiment, sound was detected very occasionally and at random. This phenomenon caused deeper investigation since we suspected that there was some relation between the sound and the failure of the machine.

Difficulty was met with in the investigation, since the frequency spectrum of the rotor's vibration seemed to be no difference from a normal one. Different instruments were tried and finally very low and frequency changeable whirl of the rotor was found. Further experiment [2] showed that both the frequency and the amplitude of the whirl were dependent on the form and the intense of the sound. The mechanism of this dependence was not clear, but the friction in the down bearing was the Most suspicious one.

2 MATHEMETICAL EXPLANATION

To understand the dynamic behavior of the rotor bearing system caused by the friction, mathematical model was built. For the convenience of simplicity, a disc-shaft system was studied, which is called Jeffcott, or De Laval rotor. From the design of the flywheel, we did some modification of the model as in figure 1. At the junction of the shaft, there is a small region of looseness. Within the

loosening region, there is friction between the shaft and the bearing, while beyond the region, the connection is supposed to be in good condition. There will be no relative motion there.

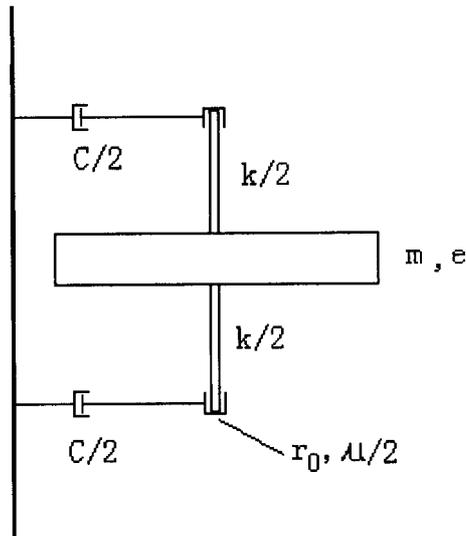


Figure 1. Rotor-bearing assembly for mathematical analysis

Let assume the loosening gap to be d , the friction force to be $f_q = mN$, the normal force on the down bearing N , then the dynamic equations are:

$$m \frac{d^2 x}{dt^2} + c \frac{dx}{dt} + kx + N \frac{m y}{r} = emw^2 \cos wt \quad (1)$$

$$m \frac{d^2 y}{dt^2} + c \frac{dy}{dt} + ky - N \frac{m y}{r} = emw^2 \sin wt \quad (2)$$

$$0 < r < d : m \neq 0 \quad ; \quad d < r : m = 0$$

where m is the mass of the rotor, c the damping, k the stiffness of the shaft, w the rotating speed which is supposed to be maintained in constant by the driver, e the eccentricity of the unbalance, (x,y) the position of the geometry center of the disc.

We consider that at first, the lubrication is perfect, i.e. $f_q = 0$. Numerical simulation [3] showed that the vibration amplitude was small, frequency of the vibration was the same as that of the rotating frequency. Then if some perturbation causes the lubrication to break down, a friction force is introduced in the tangential direction. From the numerical result we knew that the whirl of the rotor experienced difference states according to the value of the friction. See figure 2(a)-2(d).

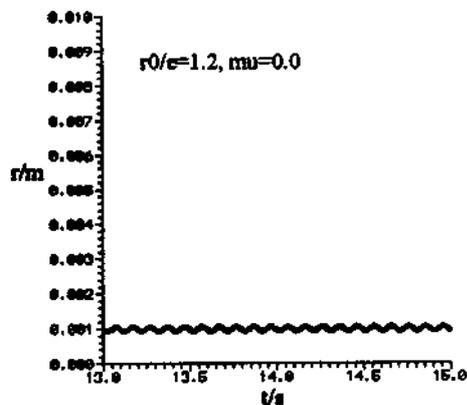


Figure 2. (a) Whirling amplitude history of the rotor without friction (numerical result)

The dominant equations (1) and (2) are nonlinear for non-zero friction. We are interested in how the value of f_q affects the whirl. From figure 2(a)-2(d) we can see that the whirl of the rotor shifts to the rotor's natural frequency (6.3 Hz) gradually as the friction increases. Finally the whirl is dominated by the natural frequency instead of the rotating frequency. Also, the whirling amplitude does not increase linearly with the friction.

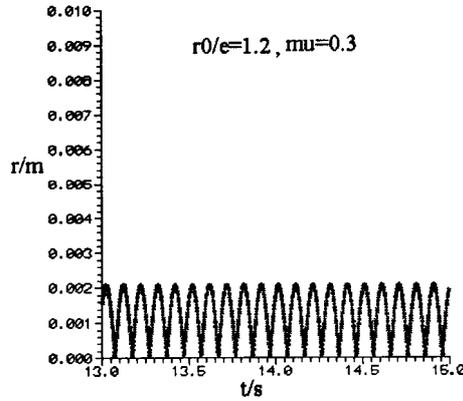


Figure 2. (b) Whirling amplitude history of the rotor with medium friction (numerical result)

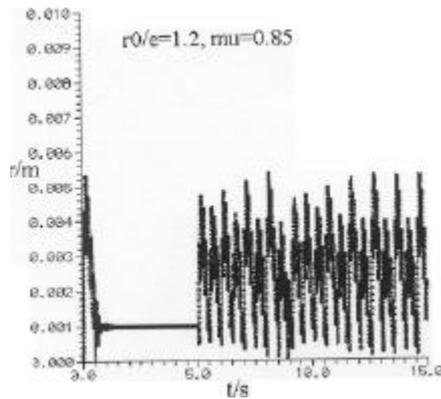


Figure 2. (c) Whirling amplitude history of the rotor with severe friction (numerical result)

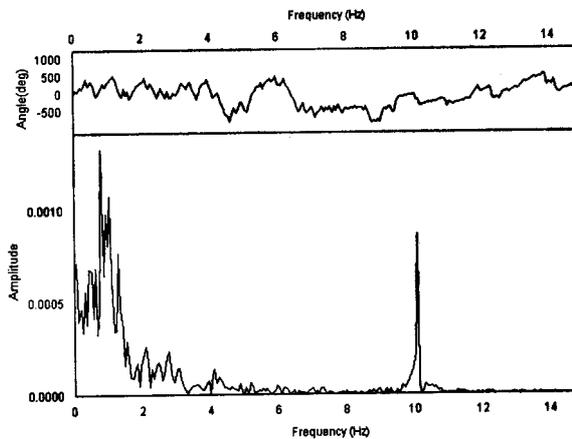


Figure 2. (d) FFT spectrum of the rotor's vibration (numerical result)

From the numerical study we conclude that:

The sound and low frequency whirl of the rotor is mostly possibly caused by the imperfect lubrication of the bearing. The whirling frequency changes according the value of the friction force, but

will finally be attracted to the natural frequency of the rotor by increasing friction. The whirl amplitude increases with the friction, but not linearly.

Bearing this in mind, we completed further experiment on this problem. We found that most phenomena observed in the experiment (figure 3) could be explained using the simple dynamic model. These phenomena were hard to understand because the real design is complicated. The whirl frequencies were mixed in a narrow band, which could not be separated without the help of the mathematical model.

3 ENGINEERING SOLUTION

The next step we were facing was how to detect this unwanted whirl, which was thought to be one of the main causes of the machine damage. It was difficult to demonstrate the very low frequency of the whirl using FFT analysis. On the other hand, the sound seemed to behave quite identically. Different states of whirl had respective sound. Considering that in normal operation situation, the sound detection was more convenient way, it was our initiation to diagnose the whirl by the sound.

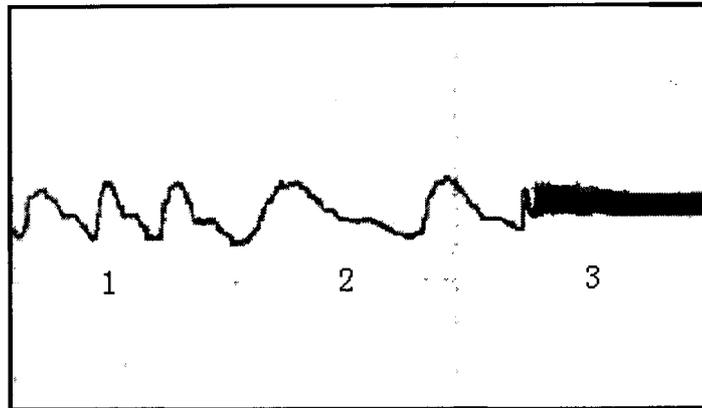


Figure 3. Experimental data of the whirling history (1-severe friction model 1, 2-severe friction model 2, 3-medium friction model 3)

It was comparatively easier to recognize different characters of the sound by human ear. For computer, this work was not so easy. We have to firstly separate the sound from the Signal which is a mixture of the vibration as well as the noise of the surroundings. Then the sound would be classified in different states, which were supposed to be related to different stages of the friction. Also, because the random and time-dependant properties of the friction, an intelligent system should be built for the analysis. This last step is still under development.

4 SUMMARY

In this paper, we have shown:

- how a common problem of friction related to a particular engineering machine research,
- how the experiment observation leads to a question worth of deep investigation,
- how the numerical analysis can help us to understand the phenomena,
- and finally, how the studied results be put to engineering solution.

REFERENCES

- [1] J.F. Mottershead, Vibration and friction-induced instability in disks, *The shock and Vibration Digest*, 30(1)(1998) 14-31
- [2] X.Z. Zhang, D.Z. Zhai, X.J. Dai, J.P. Dong, Vibration of a rotor induced by bearing friction, *Report of Tsinghua University*, 1998
- [3] X.Z. Zhang, Z.C. Feng, Nonlinear Vibration Phenomena of a rotor with a stator caused by initial perturbation, submitted to *J. Of Sound and Vibration*

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