AN ASEISMATIC CONTROL AND EVALUATION FOR ACTIVE MAGNETIC BEARING EQUIPPED ROTORS

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ABSTRACT

Up to now, any rotating machine equipped with active magnetic bearing (AMB) is not employed in nuclear plants because of its low suspension stiffness. The wide application of AMB requires an aseismatic evaluation with respect to AMB rotor vibrations caused by actual earthquakes. In this paper, a flexible rotor supported by AMB is selected for this purpose. The shaking test using actual earthquake Kobe and El Centro waves was completed and measured for the vibration evaluation. The corresponding simulation by models obtained from the quasi-modal method is also completed.

According to these experimental and theoretical results, response vibrations of AMB rotors are very severe compared with conventional oil lubricated bearing. In order to reduce the response severity against earthquakes, we propose an additional feed forward control method, which is proportional to the signal detected by the accelerometers attached to the bearing housings. Since this additional control can act as the cancellation of rotor vibration generated by the earthquakes, AMB rotor vibrations are successfully suppressed at a low level. The effectiveness of this AMB control method for earthquake induced vibrations is demonstrated.

INTRODUCTION

Aseismatic evaluation for rotating machinery has been subjected to several types of rotors settled in nuclear plants, such as pumps, compressors, fans, centrifuges and so on. The related studies on aseismatic evaluations concerning rotordynamics have accelerated the development of computational codes to simulate rotor response analysis excited by actual earthquake agitation[1]. The corresponding exciting tests are also executed by shaking rotor systems placed on a table moving according to several representative acceleration waves of actual earthquakes[2]. For the most part, these turbo rotors are supported by oil lubricated bearings having high support stiffness.

Active Magnetic Bearings (AMB) are a new type of bearings designed to maintain the rotor shaft at a neutral position without contact. This new bearing, which utilizes magnetic levitation technology, has been applied not only to small rotors, but also to large industrial rotors (e.g., turbines and compressors). Since the suspension stiffness of AMB is so low, the rotor is easily

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excited by external agitations. An aseismatic evaluation is thus required for AMB rotor applications to nuclear engineering[3]. For this purpose, in addition to the usual control for levitation and rotation, we propose an optional control method for lowering the response sensitivity against earthquake agitation. It is realized by a feed forward excitation technique according to the detected acceleration signal measured on the bearing housing. This technique cancels earthquake excitation and reduces vibration response.

An idea of the feed forward cancellation is already reported in mechatronics engineering. For instance, a hard disk drive includes the feed forward control to improve the positioning accuracy [4]. The vibration reduction of the AMB rotor applied the state space control model combined with the feed forward technique for random agitations[4]. In our study, a feed forward cancellation to seismic agitation is presented for a practical design solution to improve seismic reliability of the AMB rotors.

In this paper, an AMB test rotor simulating typical industrial turbo rotors is selected for aseismatic evaluation. The shaking test using actual earthquake Kobe and El Centro waves is carried out and the response vibrations are evaluated. The corresponding simulation by models obtained from the quasi-modal method is completed[5] and the vibration responses are analyzed numerically. These experimental and theoretical results indicate that maximum response vibrations of AMB rotors are severe compared with oil bearing type conventional rotors. In order to compensate for this drawback, a feed forward excitation control technique is introduced. The comparison of the data with and without the feed forward excitation reveals that this control is effective to guarantee safe operations under earthquake agitations.

AMB TEST ROTOR

A flexible rotor having a disc is selected for our test, as shown in Fig.1. The rotor is approximately 800 mm in length and 6.9 Kg in weight. The rotor rotates by a motor through a flexible coupling which can maintain the rotor shaft at a neutral position in the axial direction. AMBs support the rotor in the radial directions on both ends with a bearing span of 560 mm. Both bearings are called side 1 and side 2, respectively, as viewed from the motor. The diameter of the AMB journal is 30 mm and the one side clearance of the AMB is 0.5 mm. In order to avoid the rubbing of the rotor with the stators, the vibration should be less than 0.25 mm of the touch bearing gap.

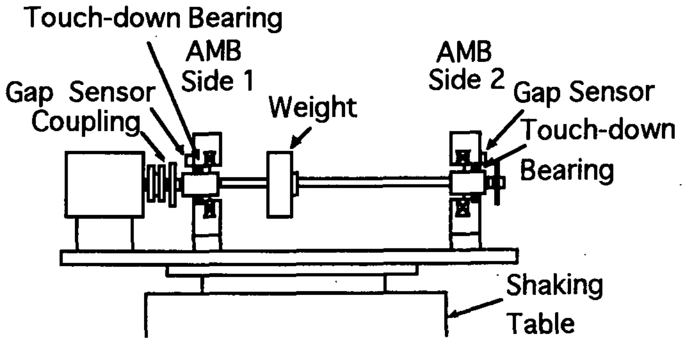


Fig.1 AMB Test Rotor

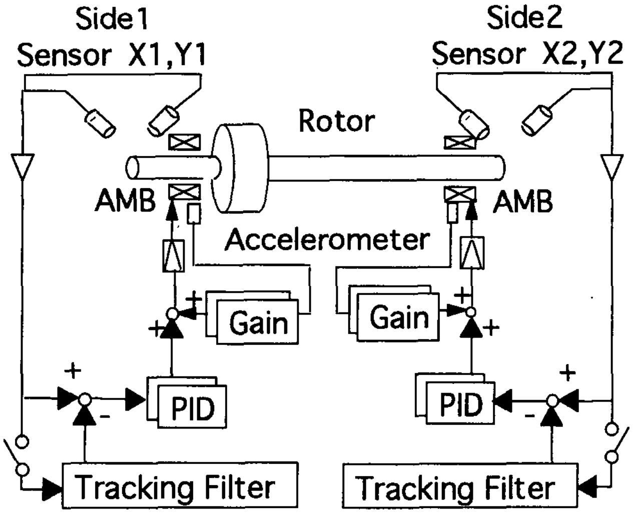


Fig.2 AMB Controller Layout

Our usual control system is described with the rotor as shown in Fig.2. The control networks are independently laid out with the same specification for each X and Y direction of the left and right bearings. It is called 4 axis decentralized control system excluding an axial control device. The AMB control for levitation and unbalance vibrations is due to PID control theory. We optionally selected the control of automatic balancing system (ABS[7]), ie, N-cut in other words, by switching the usage of the tracking filter, as indicated in Fig.2. A typical example of the unbalance vibration response curves is shown in Fig.3. We can see the rigid mode critical speeds indicated by Nc1 and Nc2, around 1800 rpm with well damped amplitude. The sharp peak of the resonance vibration seen at 5000 rpm is a flexible bending mode, called Nc3, which behaves as the free-free bending mode shape. As indicated in this response curve, the critical speeds of the rigid modes are generally designed to be placed over the seismic excitation frequency domain, ie., higher than 20-30 Hz

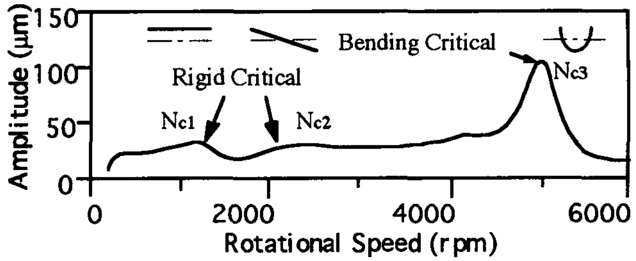


Fig.3 A Typical Unbalance Response Curve

CONCEPT OF SEISMIC VIBRATION CONTROL

First of all, we consider a simple vibrating system as shown in Fig.4 in order to clarify the fundamental concept of our idea for the AMB vibration control against the earthquake excitation. As seen in this system with one degree of freedom, a mass is supported by a spring and a damper, simulating PID functions of AMB controller. The equation motion is described with respect to the relative displacement x as follows:

$$m\ddot{x} + c\dot{x} + kx = -m\alpha(t) + F(t) \tag{1}$$

This relative displacement x is measured by the AMB displacement sensor. The seismic acceleration α(t) is measured by strain gauge type of accelerometers. An input control force is hence noted by F.

Our vibration control method is to totally eliminate excitation force denoted in the right hand side of Eq.(1):

$$F(t) = m\alpha(t) \tag{2}$$

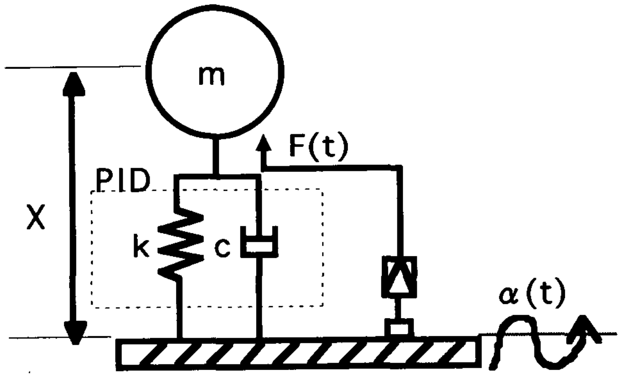


Fig.4 Foundation Excitation of 1 DOF System

This input force required in the above equation is realized by a feed forward excitation (FF) technique of AMB control. An actual network corresponding to the input control excitation is expressed by implemental parts of accelerometers in addition to the usual PID controller, as shown in Fig.2. The acceleration waves measured on bearing housings at both ends are transmitted to the AMB control cabinet and this signal, with a certain proportional gain, is fed to the power amplifier to generate the magnetic exciting force independently from the PID main control. Consequently, the addition of both commands from PID loop and the feed forward excitation loop provides the coil current to generate a total magnetic force. The proportional gain required for the feed forward excitation should be determined by considering electronical device parameters, the combined controller command, and nonlinearity of magnetic force due to the bearing gap and current dependencies. Instead of

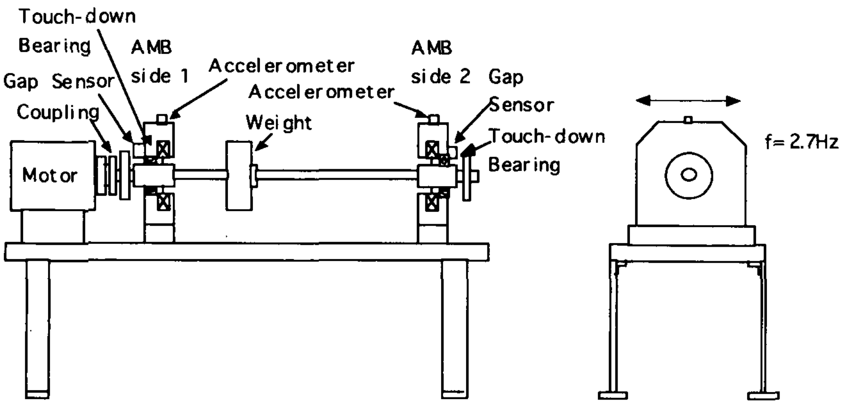
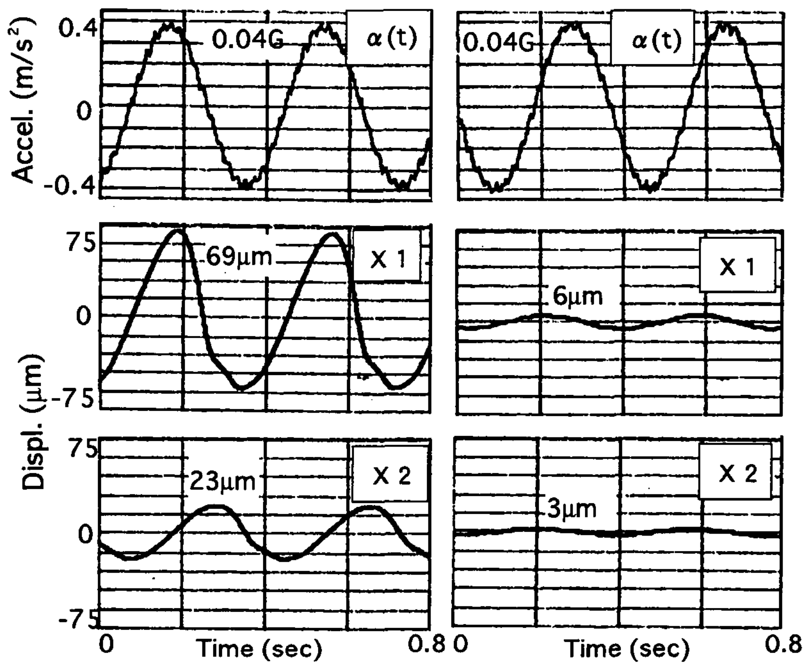


Fig.5 Test Rotor Bed on Flexible Supports

these theoretical approaches to determine the required gain, we manually adjusted it.

For this reason, we supported the rotor bed with a flexible stand as shown in Fig.5, prior to the shaking test. As seen in the side view of this layout, the stand vibrates in a horizontal way with the natural frequency of 2.7 Hz. In this situation, we hit the bed and measure the rotor vibrations as shown in part of Fig.6 (a) PID . The response vibrations significantly reacted. In the following step, we activate the feed forward control loop and vary the gain manually to reduce the vibration to zero as shown in part of Fig.6 (b) PID+FF . The comparison between the response vibrations with and without the feed forward excitation demonstrates beneficial adjustments of the gain value.



(a) PID (b) PID+FF

Fig.6 Tune of Feed Forward Excitation Gain Parameter

SEISMIC SHAKING TEST

Test Procedures

This rotor is set on a shaking table to simulate earthquake waves. Our test employs six waves, ie, up-down (UD), east-west (EW) and north-south (NS) directions of El Centro and Kobe earthquakes. The dominant frequencies of El Centro is lower compared to Kobe. The outline of each earthquake

Table 1 Seismic Waves used for our Test

Seismic Wave	Direction	Max (m/s²)
Kobe (17.01,'95) measured at Kobe Marine Meteorological Observatory	UD	3.32
	EW	4.76
	NS	8.10
El Centro (18.05,'40) measures at El Centro valley	UD	2.06
	EW	2.08
	NS	3.40

wave is listed in Tab.1.

The operational conditions of the rotor being subject to the seismic agitation are below.

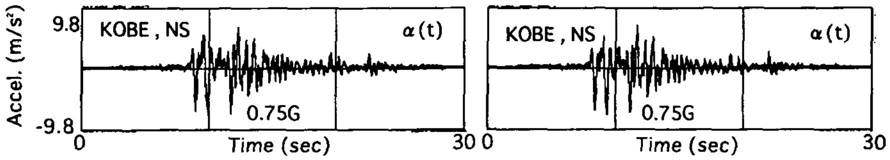
(1) 0 rpm (no rotation) PID suspension

(2) 6000 rpm (rated rotation) PID suspension (3) 6000 rpm PID + ABS suspension

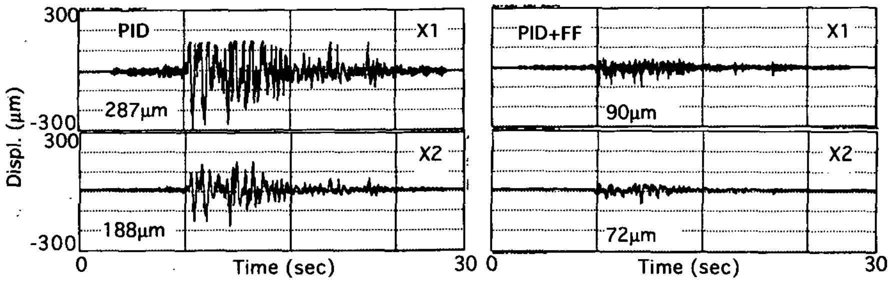
The shaking test is executed in these three cases. In each case, we increase the shaking magnitude of the earthquake wave step by step up to approximately 1G of the acceleration.

Seismic Excitation Test without Control

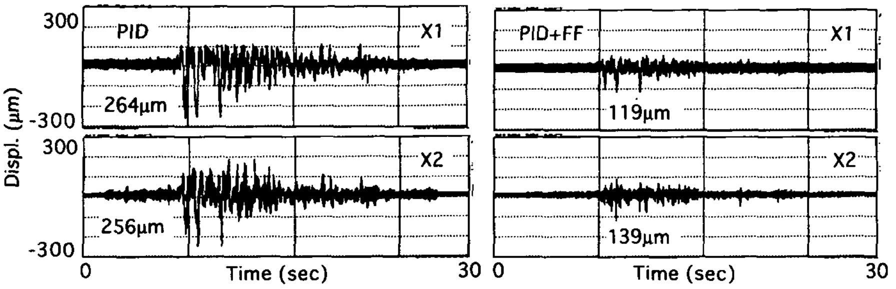
Typical data from the seismic shaking test are displayed in Fig.7 (a). The input seismic wave of NS direction of the Kobe earthquake is shown in (1) of the top figure of Fig.7 (a). The corresponding response vibrations are laid out in (2) of no rotation (0 rpm) with PID control, in (3) of rated speed rotation (6000 rpm) with PID, and in (4) of with PID plus ABS. Each



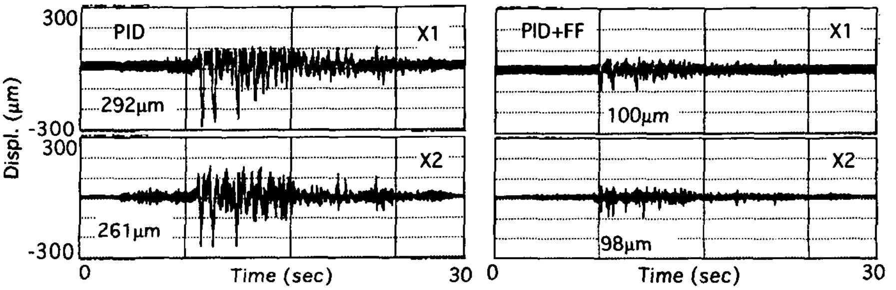
(1) Seismic Wave (KOBE , NS) (1) Seismic Wave (KOBE , NS)



(2) Rotor Vibration (PID,0rpm) (2) Rotor Vibration (PID,0rpm)



(3) Rotor Vibration (PID,6000rpm) (3) Rotor Vibration (PID,6000rpm)



(4) Rotor Vibration (PID+Ncut,6000rpm) (4) Rotor Vibration (PID+Ncut,6000rpm)

(a) PID (b) PID+FF

Fig.7 Seismic Excitation Response and Control (Test) response curve of (2)-(4) has rotor vibration waves measured at side 1 and 2 bearing sensors, respectively. Since the rotor natural frequency, Nc1, is much higher than seismic excitation frequencies and the rotor is seen as a rigid rotor, the response waves are similar to input seismic waves. Thus, the rotor vibration can be easily evaluated by static deflection problems concerning the seismic load.

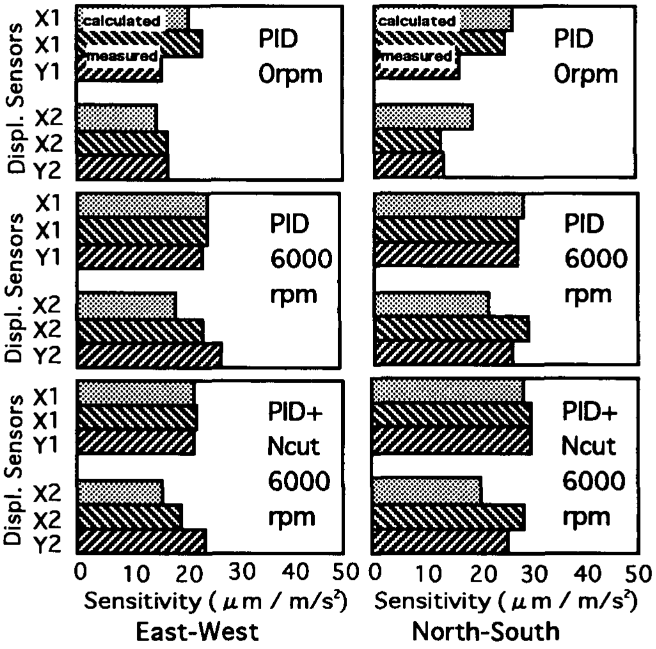


Fig.8 Response Sensitivity (Kobe)

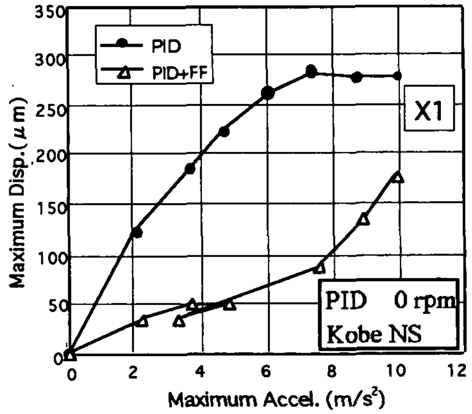
The magnitude of the input seismic wave is approximately 0.75 G maximum as shown in (1) of Fig.7 (a). Roughly stated, the maximum values of each vibration response waves are distributed in the range of 188 - 292 μm as seen in (2)-(4) of the figures. In this manner, we summarized each shaking data in a ratio, ie, the maximum response vibration displacement / the maximum input acceleration magnitude. Examples of these relationship are plotted in "PID" of Fig.9. This result of the slopes indicates the response sensitivity against the earthquake agitation, as shown in "measured' of Fig.8. The experimental value of the response sensitivity is approximately 300μm / G.

If we assume the rigid body of the rotor and then estimate the static deflection, the following equation is approximately provided the sensitivity

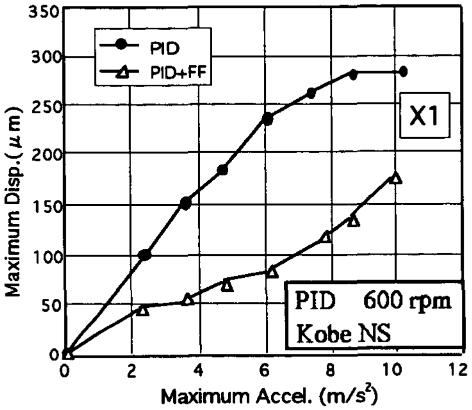
$$kx = m\alpha(t) \qquad (3)$$

In this case with the lowest natural frequency of 25 Hz, the response sensitivity is optimistic in the vicinity of 290 μm / G.

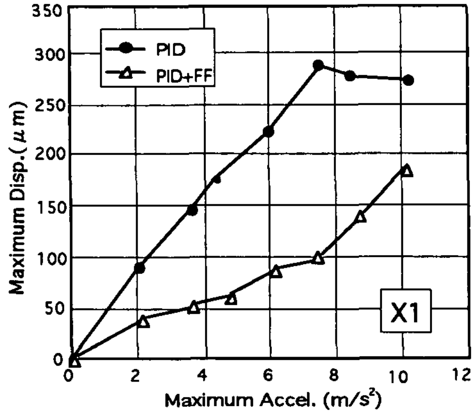
Since the gap of the touch down bearing is 250 μm and the sensitivity is estimated by 300 μm / G of a pessimistic value from Fig.8, the rotor can rotate without rubbing under the earthquake agitation with the magnitude less than about 250 / 300 = 0.83 G class. This value seems to be



(1) PID 0 rpm(KOBE , NS)



(2) PID 6000rpm(KOBE , NS)



(3) PID+Ncut 6000rpm(KOBE , NS)

Fig.9 Effect of FF Control (Test)

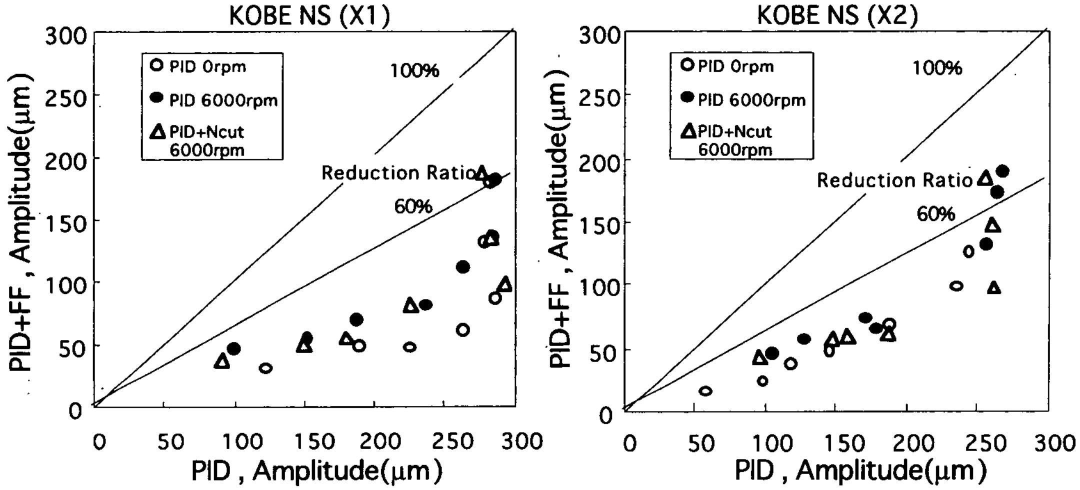
sufficient to use for the AMB rotors in nuclear plants. Nevertheless, the most powerful earthquake induced rotor vibrations can reach the gap of the touch bearing causing occasional rubbing vibrations and possible critical damage. This kind of critical situation should be avoided for safety reasons.

In fact, since the AMB stiffness is smaller than the oil lubricated stiffness by about 10-100 times, the corresponding vibration response severity becomes very large in reverse proportion. In order to further improve the response severity induced by the seismic excitation, development of an additional control method should be created.

Seismic Excitation Test with Control

The typical example of the shaking test data with the feed forward control are provided in Fig.7 (b), in comparison with no FF control. The rotor vibration response at stop was well attenuated due to the feed forward control. This effectiveness is also accepted by data obtained at rotation.

The comparison of effectiveness of this control is summarized in Fig.9. The horizontal axis indicates the maximum value of the table acceleration of the inputted earthquake acceleration wave with variable magnitude. At each shaking, the vibration response waves are detected and



(1) KOBE , NS

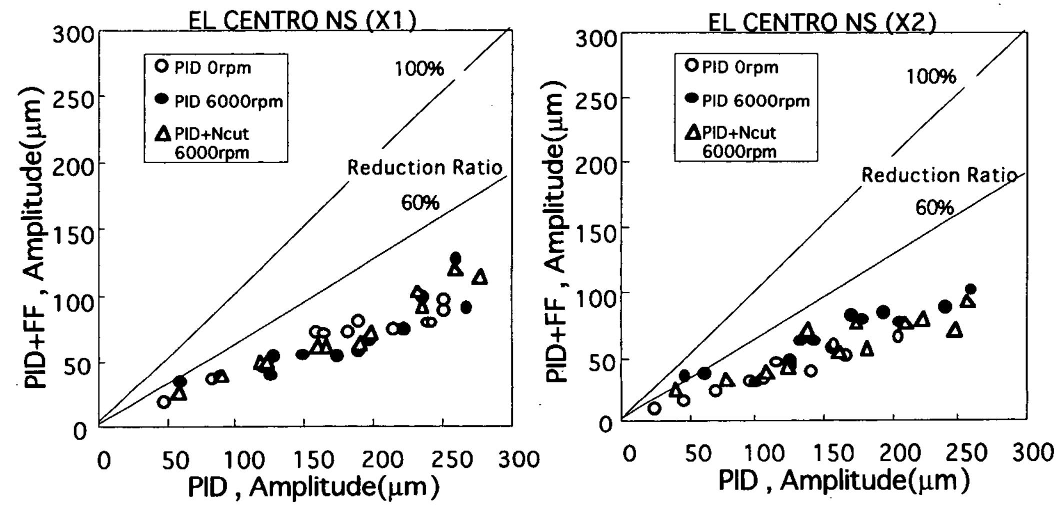
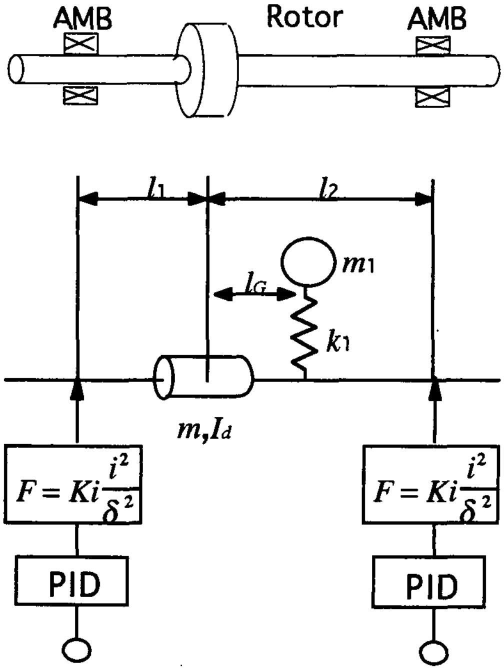


Fig.10 Response Reduction Ratio by FF Control

the maximum values of the response waves are measured. The relationship between input acceleration magnitude and the maximum response vibration level are plotted in these figures. In the case of no rotation, the vibration reduction is significantly achieved as shown in Fig.7 (1). Even during the rotation, evidences of the vibration reduction are shown in Fig.7 (2) and (3). Comparison of the data is rearranged as shown in Fig.10. When the magnitude of the input accelerations is rearranged at the same, maximum values of the response vibration displacements with and without the control are plotted on X axis and Y axis, respectively. The slope of the line including these points indicates the vibration reduction ratio. According to this comparison, the effectiveness of the control by the vibration reduction ratio will be approximately 60%.



m=6.64 kg
m_1=0.5 kg) 7.14 kg
I_d=0.385 kgm^2
l_1=0.151 m
l_2=0.409 m
l_G=0.230 m
ki=1.3×10^{-5} Nm^2/A^2

Fig.11 Models of Test Rotor

NUMERICAL SIMULATIONS

Rotor Model

The rotor is reduced to three degrees of freedom system by quasi-modal model, as shown in Fig.11. The centerline having a mass indicates a rigid bar spanned on both the left and right AMBs. A mass noted by m1 represents the pure bending motion of the shaft. The figure includes the model of AMB with PID control considered by the nonlinear magnetic force:

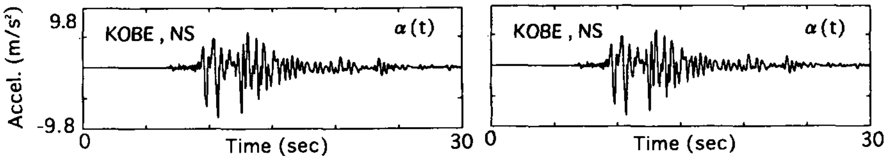
$$F = Ki * I^2 / \delta^2 \qquad (4)$$

Simulation Results

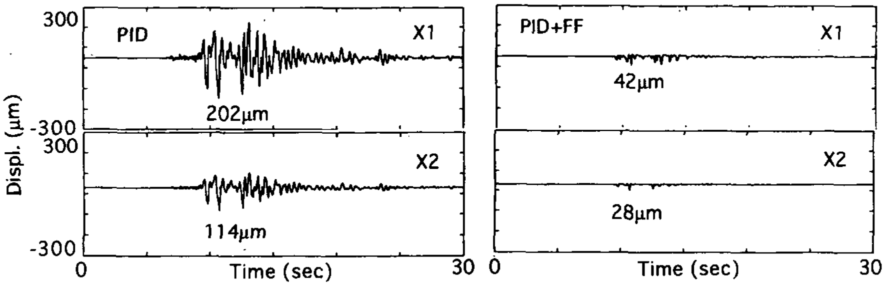
The vibration responses are analyzed with and without the control. Several examples are shown in Fig.12, for the NS directional wave of the Kobe earthquake (1). Since this rotor behaves as a rigid rotor against low exciting frequency domain of the earthquake waves, the difference between the input acceleration wave and the rotor response vibration waves is insignificant.

The vibration response severity is summarized from these simulation waves and the result is presented in Fig.7 which is fairly accepted with the experimental data. The vibration at rest (no rotation, (2)) is perfectly attenuated by the control. During the rotation in (3), the centerline of the vibration wave became widened because of unbalance vibration components included. As seen in the case (4) of PID plus ABS operation, this unbalance vibration is excluded and only seismic vibration response appears. In any case of these three conditions, ie., rotation or no rotation, PID or PID+ABS, the response vibrations are well attenuated for seismic agitation. These numerical simulation data is summarized in "calculated' of Fig.8.

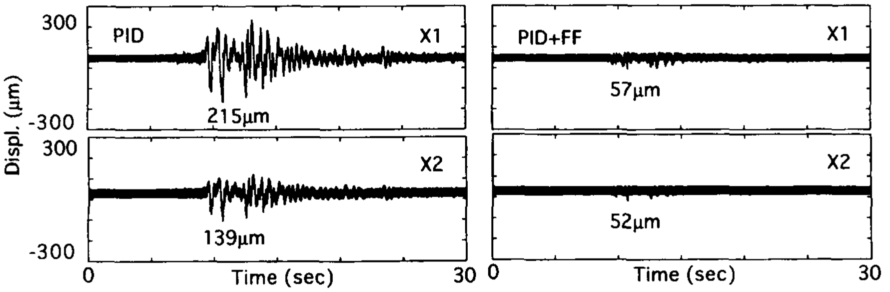
The comparison of the response with and without the control is the most interesting as shown in "PID+FF" of Fig.9. As seen in this comparison, the response severity improvement is expected by this feed forward technique.



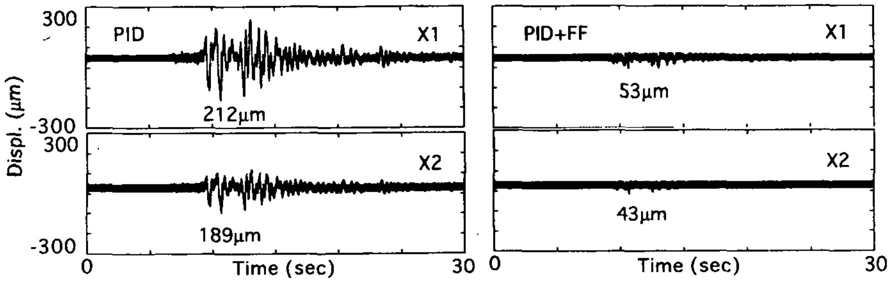
(1) Seismic Wave (KOBE , NS) (1) Seismic Wave (KOBE , NS)



(2) Rotor Vibration (PID,0rpm) (2) Rotor Vibration (PID,0rpm)



(3) Rotor Vibration (PID,6000rpm) (3) Rotor Vibration (PID,6000rpm)



(4) Rotor Vibration (PID+Ncut,6000rpm) (4) Rotor Vibration (PID+Ncut,6000rpm)

(a) PID (b) PID+FF

Fig. 12 Response Simulation of Seismic Excitation

The effectiveness is numerically evaluated in each case as shown in Tab.2. Consequently, the introduction of this feed forward excitation control technique could be available in any PID situation. The simulation provides the vibration reduction ratio due to the control by 50%, optimistically.

CONCLUSIONS

The evaluation of the response severity against seismic excitation is carried out for AMB equipped flexible rotors. A general design guideline to avoid the resonance or rubbing vibrations caused by earthquake agitation states that the lowest natural frequency of rigid modes is to be set larger than 20 - 30 Hz. Even if the AMB rotor is designed in this manner, the response severity is still higher than oil lubricated rotors.

A technique called feed forward excitation (FF) is introduced to the AMB rotor for the reduction of vibration response severity against the seismic agitation in addition to the usual PID control. It is realized by the addition of a controller network for inputting magnetic force being proportional to the acceleration signal detected on the bearing housing. The efficiency of this control is experimentally and numerically accepted by comparing the response vibrations of PID control only and of PID plus FF control. The vibration reduction effect of this FF control is experimentally estimated by 60%.

Table 2 Vibration Reduction Effect due to Feed Forward Control

Seismic Wave	AMB Control	Rotation (rpm)	Maximum Vibration Displacement (μ m)				Vibration Reduction Ratio (%)	
			Not FF		FF			
			X1	X2	X1	X2	X1	X2
Kobe UD	PID	0	171	111	76	12	44	11
	PID	6000	131	153	76	70	58	46
	PID+Ncut	6000	141	129	82	91	58	71
El Centro UD	PID	0	65	43	21	13	32	30
	PID	6000	89	53	36	28	40	53
	PID+Ncut	6000	80	40	35	31	44	78

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