DEVELOPMENT OF COMPENSATOR FOR ACTIVE MAGNETIC BEARING ROTOR SYSTEM BY USING MODIFIED BANG-BANG CONTROLLER WITH DEAD ZONE ELEMENT

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ABSTRACT
This paper aims at proposing a new modified Bang-Bang controller which is supplemented to ordinary PID controller of the rotor system supported by AMB as compensator. Dead zone element is introduced into the previous modified Bang-Bang controller in order to achieve the less control energy.

Since the control force by the previous modified Bang-Bang controller is proportional to the vibration amplitude of the flexible rotor measured by displacement sensors, the control force is generated even if the vibration amplitude of the flexible rotor is suppressed under the allowable level or the sensor noise level. Therefore, the control force by the previous modified Bang-Bang controller can be improved by introducing the dead zone element.

INTRODUCTION
Recently, hardware requirements for rotating machinery become severe year by year, for example, not only reduction in its size and weight but also high speed rotation and less unbalance response are required simultaneously. One of the attractive solutions of these requirements is the installation of active magnetic bearing (AMB). AMB could satisfy above mentioned severe requirements. Therefore it can be widely applied to industrial rotating machinery. An instability compensator for AMB controller is indispensable. PID controller is usually used for the vibration suppression of the rotor supported by AMB and it is sufficient for only rigid rotor.

Authors previously proposed the instability compensator which is supplemented to ordinary PID controller to improve the stability of the control loop for the flexible rotor system [1,2]. In the previously proposed compensator, the modified Bang-Bang control with the time varying magnitude of the control gain was taken as the control method instead of the notch filters. The gain is proportional to the vibration amplitude of the flexible rotor.

A new modified Bang-Bang controller which is supplemented to ordinary PID controller of the rotor supported by AMB is proposed here. In the proposed method, dead zone element is introduced into the previous modified Bang-Bang controller in order to achieve the less control energy. The effectiveness of the dead zone element will be shown by some experimental study.

NEW MODIFIED BANG-BANG CONTROLLER WITH DEAD ZONE ELEMENT

Previous Modified Bang-Bang Controller
A modified Bang-Bang controller was proposed as a compensator in addition to the traditional PID controller by the previous authors' work [1,2]. The previous modified Bang-Bang controller is based on the velocity dependent switching gain. The magnitude of the gain is a time dependent function that is proportional to the amplitude of the unbalance response of the rotor. The previous modified Bang-Bang controller is expansion of velocity feedback. The control power of the Bang-Bang controller depends on the amplitude of the unbalance response of the rotor. When this method is applied to the rotor system, even if it occurs a time lag, it does not effect on high-frequency oscillation. The effective value of the unbalance response is used instead of the amplitude of the response as the magnitude of the gain. Then, the control law of the previous modified Bang-Bang controller is given by the following form.

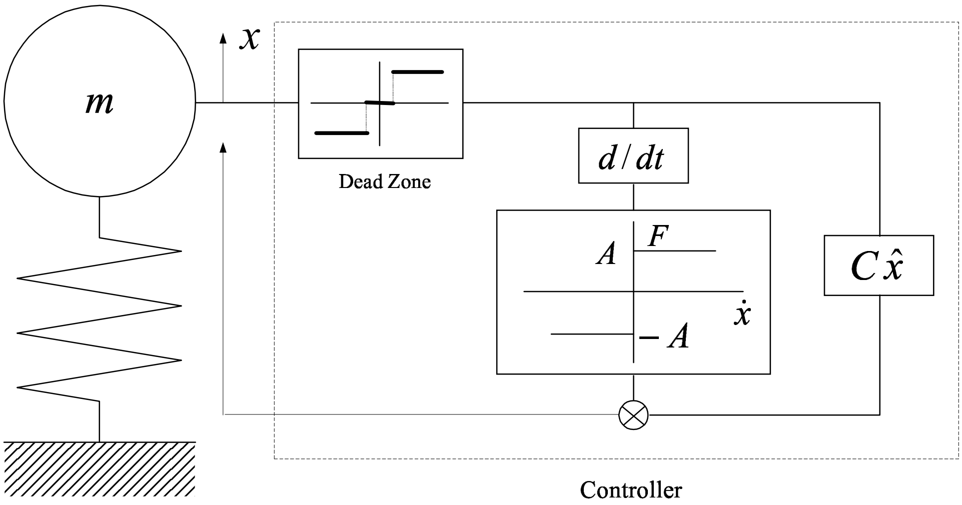


FIGURE1: 1-DOF Model for the New Modified Bang-Bang Controller

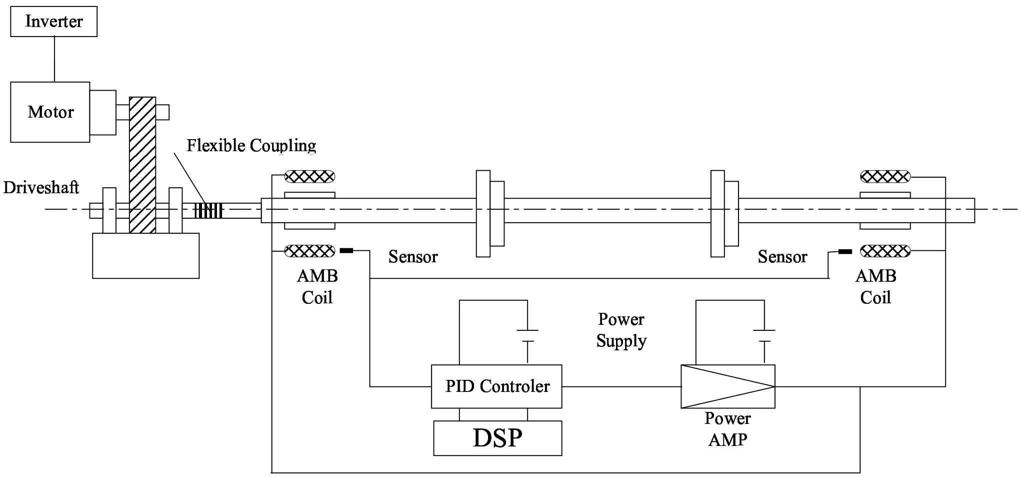


FIGURE2: Rotor System supported by AMB

$$F = A|\hat{x}|\,\mathrm{sgn}(\dot{x}) \qquad (1)$$

where A is a constant. $|\hat{x}|$ is the gain which is the absolute value of the effective value of the unbalance response measured by the displacement sensor at the AMB. $\mathrm{sgn}(\dot{x})$ denotes "sign of" and represents a function having the value +1 if its argument $\dot{x}$ is positive and the value –1 if its argument is negative.

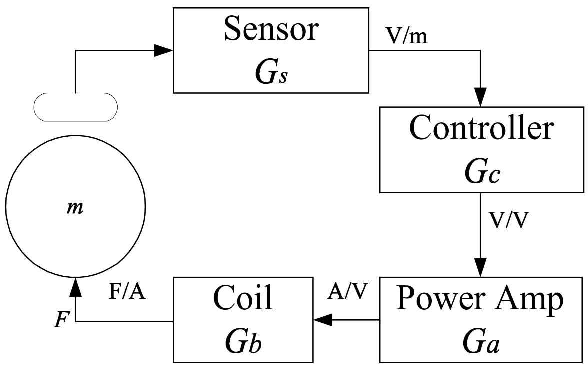


FIGURE3: Control Loop for AMB

New Modified Bang-Bang Controller

New modified Bang-Bang controller with dead zone element for reducing the control energy is proposed here. A single degree-of-freedom model for the new modified Bang-Bang controller is shown in Figure 1. In the proposed method, the control input is cut off when the measured amplitude of the unbalance response of the rotor is suppressed under the allowable level such as the steady state response level obtained by well-tuned PID controller or the sensor noise level.

The control energy can be dramatically reduced at the steady rotating speed in which the amplitude of the response is very small.

The following control law of the new modified Bang-Bang controller is proposed.

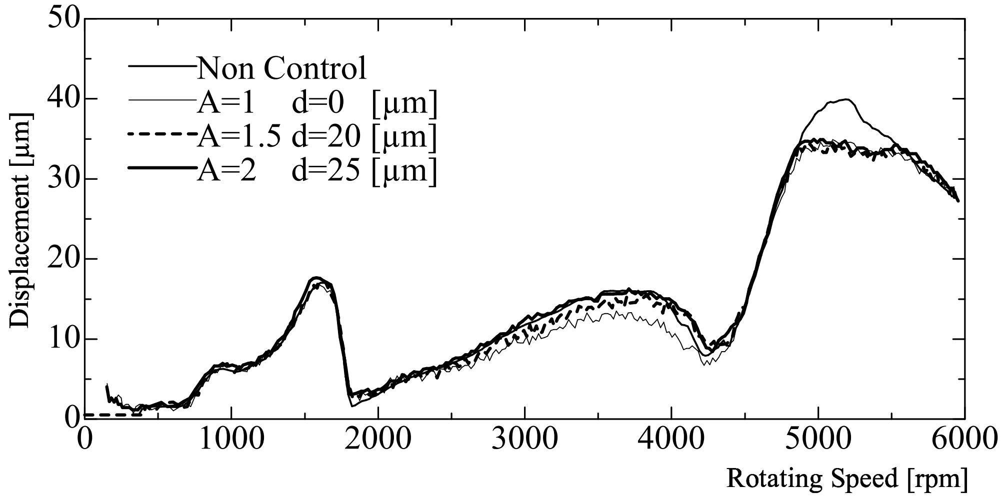


FIGURE4: Resonance Curve

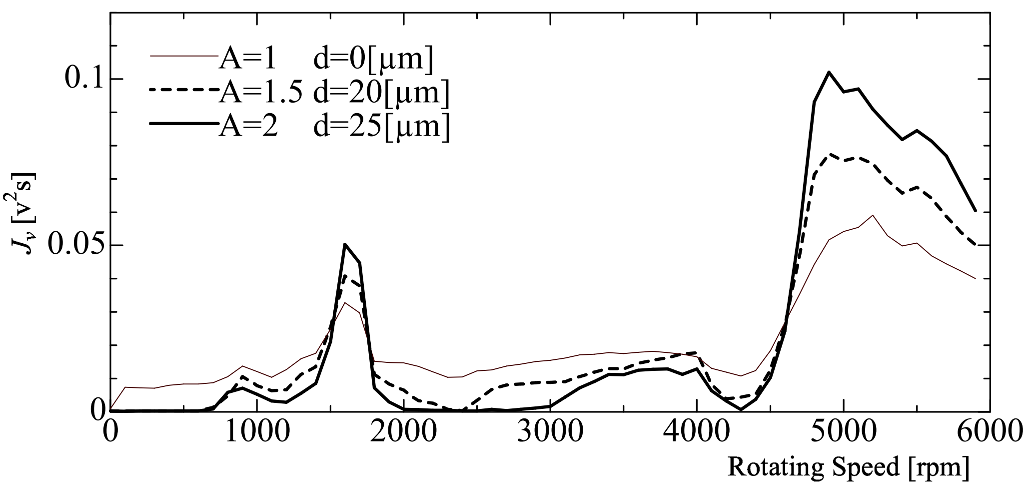


FIGURE5: Evaluation of Control Energy

$$F = A|\hat{x}|\,\mathrm{sgn}(\dot{x}) \qquad (x \ge d) \qquad (2)$$

$$F = 0 \qquad (x \le d) \qquad (3)$$

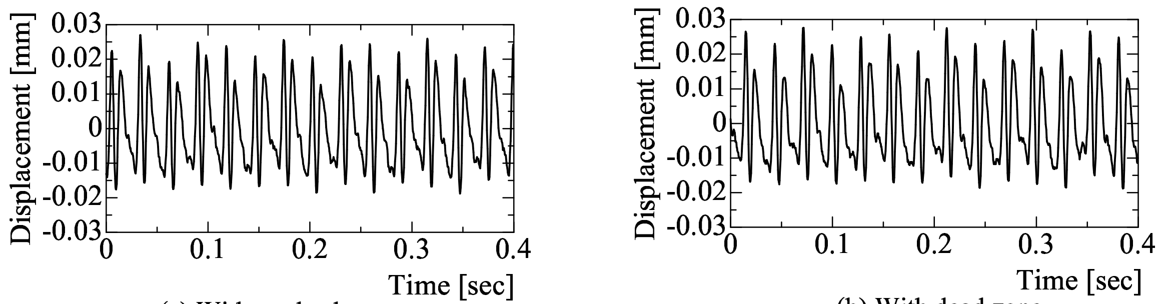
where d indicates the magnitude of the dead zone element.

EXPERIMENTAL SETUP

A flexible rotor is supported by two sets of the active magnetic bearings. Figure 2 shows the experimental equipments. Figure 3 shows the controller block diagram of the control loop. It has four displacement sensors and eight pieces of coil in both bearings. The displacement sensor signal is transmitted to PID controller and DSP. PID controller is used for levitation control, and DSP is used for unbalance response compensator. Characteristics of the AMB depend on a frequency response of PID controller. The control output from DSP is added to PID controller output and these controller output signals are inputted to the power amplifier. The electric current supplied from the power amplifier drives AMB. The control force is proportional to the square of the amplitude of the driving electric current.

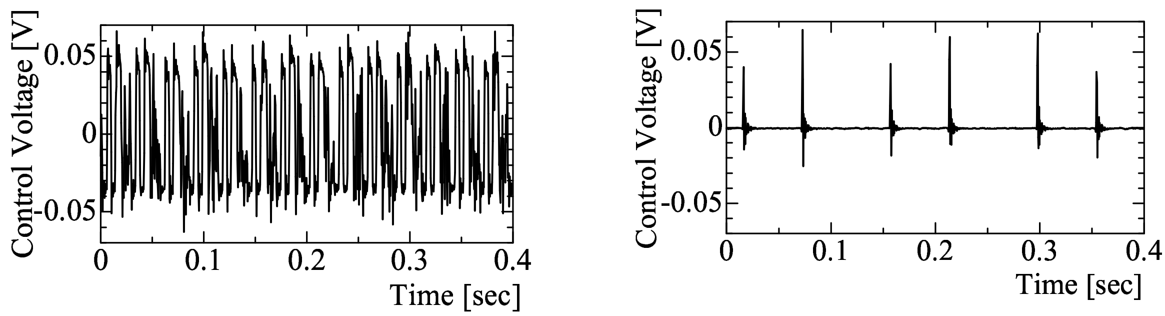
EXPERIMENTAL RESULTS AND DISCUSSIONS

New modified Bang-Bang controller is experimentally tested by using the above mentioned rotor system in order to demonstrate the effectiveness of the proposed method. The rotor can be rotated up to 6000(rpm) that is over the critical speed of first bending resonance of the rotor. Reduction of the control energy is evaluated by using following index J_v under restricted operating speed. Lower limit of the operating speed



(a) Without dead zone (b) With dead zone

FIGURE 6: Unbalance Response at 2100 (rpm)



(a) Without dead zone (b) With dead zone

FIGURE 7: Control Force at 2100 (rpm)

is 2000(rpm) that is 1.25 times the critical speed of the first rigid body mode of the rotor and upper limit of the operating speed is 2400(rpm) that is 0.75 times the critical speed of the second rigid body mode of the rotor.

$$J_v = \int v^2 dt \tag{4}$$

where v is control voltage applied to the power amplifier as control instruction signal from DSP. The value of the electric current driving AMB is proportional to the value of v.

Three different cases are tested. In each case, the value of the constant gain A is tuned to the different magnitudes of the dead zone element: $d = 0\,(\mu m)$, $20\,(\mu m)$ and $25\,(\mu m)$, in order to achieve the same amplitudes of the unbalance responses of the rotor. The resonance curve is shown in Figure 4. The value of the control energy evaluation is shown in Figure 5 for various rotating speed from 0(rpm) to 6000(rpm) including the restricted operating speed. In the restricted operating speed, the same amplitudes of the unbalance responses of the rotor with different values of d are achieved (Figure 4). Figure 5 shows that the value of the control energy evaluation is decreased corresponding to increase the magnitude of the dead zone element. Time histories of the rotor with and without dead zone element at 2100(rpm) are shown in Figure 6(a) and 6(b), respectively. Similarly, time histories of the control input with and without dead zone element at 2100(rpm) are shown in Figure 7(a) and 7(b), respectively. The modified Bang-Bang controllers with and without dead zone element obtain the same unbalance responses of the rotor (Figure 6). The dead zone element hasn't bad influence on the response because its magnitude is small. Under such condition, control voltage is dramatically reduced by introducing the dead zone element into the previous modified Bang-Bang controller. In Figure 7(a), the control force is generated, however the amplitude of the response is small. On the contrary, in Figure 7(b), it isn't generated because of the existing the dead zone element. Control force is only generated when the amplitude of the response exceeds the dead zone, and then suppressing the response within the dead zone, the control signal is cut off. It is clear that the proposed new modified Bang-Bang controller can improve the control energy consumption.

CONCLUSION

A new modified Bang-Bang controller is proposed, in which dead zone element is introduced into the previous modified Bang-Bang controller. Control energy required to preserve the same unbalance response of the rotor is successfully reduced by using the proposed control method at the restricted operating speed of the rotor.

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