

Knowledge-Based Fuzzy Imbalanced Force Compensator Design for a Single Active Magnetic Bearing Suspended Rotor System

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Abstract—A fuzzy imbalanced force estimator and feed-forward controller designed by the knowledge of rotor dynamics for a single active magnetic bearing suspended rotor system was proposed to eliminate the unbalancing vibration of rotor in the paper. The variable parameters used in the fuzzy estimator are displacement and velocity of the rotor and control current of the magnetic bearing. Based on the estimating signal, a feed-forward control system is set to suppress the unbalancing vibration. The simulation and experiment results show that the proposed estimation system could accurately estimate the unbalance force and the feed-forward control system could restrain the unbalancing vibration to improving the rotational accuracy.

Keywords—fuzzy imbalanced force estimator, single active magnetic bearing

I. INTRODUCTION

Active magnetic bearing (AMB) is the essential part of the non-contact rotor systems and have been widely developed in industrial application, i.e., the spindle of machine tool, the linear motor, the flywheel energy store system, and the compound molecular pump, etc. By the reference [1], we know the AMB can't work stably without a control system. Thus the control system which contains position sensors and a traditional proportional-integral-derivative (PID) controller is the standard control system for the industries. Parameters of the PID controller are based on the system's dynamic model. But the system model can't obtain accurately and always keep in the same condition. Thus, in order to optimize the controller to make the system more stable, there are many researches working for the controllers with the unknown parameters of the AMB system. For the unknown parameters of the AMB rotor system with vibrating base, an adaptive back stepping controller was proposed and the results showed the bearable acceleration disturbance level was higher than PID controller [2]. The model uncertainty of the AMB system changed with the operating rotor speed, a linear parameter-varying controller was proposed for the time-varying AMB parameters [3]. Mainly vibration source of the disturbance is the unbalance force from the rotor. The Sliding mode control was applied to increase the robustness of the AMB system to reduce the disturbance response [4].

From these researches, we can find in such a non-contact rotor system the unbalance force is usually the other factor which induced the rotor system being unstable as the rotor running to the critical speed of the system, consequently, the unbalance compensation is needed. Moreover, if the unbalance force can be predicted, the parameters of the controller can be modified to control the system operating more smoothly [5]. A model based force estimator with an adaptive tuner for a single AMB suspended rotor system was proposed to eliminate the imbalance vibration in our early research [6]. These methods are frequency dependent because the synchronous reference signal generator has parameters that are dependent on the rotor spin rate, thus requiring continual adaptation as the spin rate varies or they are built on the linear model of the AMB system that there are parameters uncertain problem must be resolved. Therefore, this problem was tried to be solved by a traditional PID controller and a fuzzy feed-forward force compensator.

In recent years, fuzzy controller has been found to be one of the most popular controllers. A well designed fuzzy logic controller can handle uncertain information and used in the control of the AMB system which are having a complex time-variable mathematical model.[7-10] The fuzzy logic control system contains sets of variable functions which are fuzzy rules and membership functions. Generally these variables can be adjusted by the experiment results and try and error. By continuing adjust the fuzzy variable functions, the fuzzy logic control system can be the most effective controller to control the AMB systems.

In this paper, a knowledge-based fuzzy imbalanced force compensator system is proposed. The compensator system is established by the measurement of the displacement of the rotor, control current of the magnetic bearing and rotor speed. And the fuzzy rules and membership functions was established by the previously research which showed the feed-forward compensator could meliorate the rotational accuracy in the operational range. After building the fuzzy compensator system, the feed-forward control system is established. To verify the compensator system and the feed-forward control system, the simulation and experiment results was carried out.

II. MODELING OF A SINGLE MAGNETIC BEARING SUSPENDED ROTOR SYSTEM

Fig.1 shows the basic structure of the single AMB system. The rotor is suspended horizontally by an AMB in the free end and a flexible coupling in the other end connected with the motor. The rotor positions in the free end are measured by two eddy-current type sensors at the magnetic bearing location. The spinning shaft is driven by the motor. Fig.2 shows the relative positions of the coupling, magnetic bearing and the mass center of rotor. Fig.2 also shows the directions of the four degrees of freedoms of the rotor and the action positions and directions of the magnetic forces ($F_1 \sim F_4$) and the reacted forces (F_{xt} , F_{yt}) of the flexible coupling.

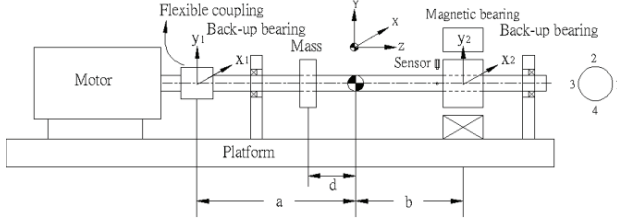


Fig.1 Structure of the single AMB system

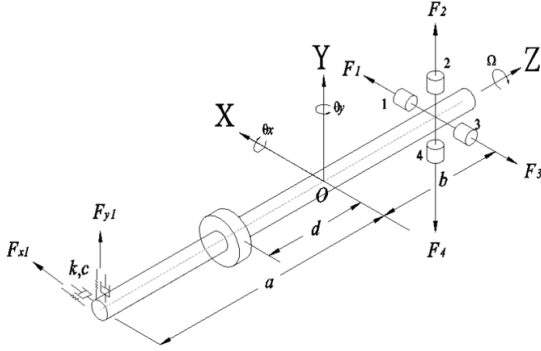


Fig.2 Geometric relationship of the single AMB system

According to the research[5], the magnetic force and the reacted forces of the flexible coupling can be expressed as:

$$\begin{aligned} F_1 - F_3 &= k_i i_1 + k_{d1} x_2 \\ F_2 - F_4 &= k_i i_2 + k_{d1} y_2 \end{aligned}$$

where x_1 , y_1 , x_2 , and y_2 are the radial displacements at the positions of flexible coupling and AMB; k_T and c_T are the equivalent stiffness and damping coefficients of the flexible coupling; k_i is the current-force coefficient and k_d is the displacement-force coefficient of AMB.

The dynamics of the system in terms of displacements in the flexible coupling and magnetic bearing locations, which can be written in matrix form as follows:

$$M\ddot{\underline{x}} + C\dot{\underline{x}} + K\underline{x} = B\underline{u} + E\underline{w} + F\underline{x}^3 + D\underline{g}$$

$$M = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}; C = \begin{bmatrix} c_T\beta_3 & 0 & \alpha_1 & -\alpha_1 \\ -c_T\beta_2 & 0 & -\alpha_2 & \alpha_2 \\ -\alpha_1 & \alpha_1 & c_T\beta_3 & 0 \\ \alpha_2 & -\alpha_2 & -c_T\beta_2 & 0 \end{bmatrix}$$

$$K = \begin{bmatrix} k_T\beta_3 & k_{d1}\beta_2 & 0 & 0 \\ -k_T\beta_2 & -k_{d1}\beta_1 & 0 & 0 \\ 0 & 0 & k_T\beta_3 & k_{d1}\beta_2 \\ 0 & 0 & -k_T\beta_2 & -k_{d1}\beta_1 \end{bmatrix}; B = \begin{bmatrix} -k_i\beta_2 & 0 \\ k_i\beta_1 & 0 \\ 0 & -k_i\beta_2 \\ 0 & k_i\beta_1 \end{bmatrix}; E = \begin{bmatrix} \gamma_2 & 0 \\ -\gamma_1 & 0 \\ 0 & \gamma_2 \\ 0 & -\gamma_1 \end{bmatrix};$$

$$D = \begin{bmatrix} 0 \\ 0 \\ -1 \\ -1 \end{bmatrix}; \underline{x} = \begin{bmatrix} x_1 \\ x_2 \\ y_1 \\ y_2 \end{bmatrix}; \underline{u} = \begin{bmatrix} i_1 \\ i_2 \end{bmatrix}; \underline{w} = \begin{bmatrix} m_p r \Omega^2 \cos(\Omega t + \theta) \\ m_p r \Omega^2 \sin(\Omega t + \theta) \end{bmatrix};$$

$$\alpha_1 = \frac{I_p \Omega a}{IL}; \alpha_2 = \frac{I_p \Omega b}{IL};$$

$$\beta_1 = \left(\frac{b^2}{I} + \frac{1}{m} \right); \beta_2 = \left(\frac{ab}{I} - \frac{1}{m} \right); \beta_3 = \left(\frac{a^2}{I} + \frac{1}{m} \right);$$

$$\gamma_1 = \left(\frac{bd}{I} - \frac{1}{m} \right); \gamma_2 = \left(\frac{ad}{I} + \frac{1}{m} \right)$$

where m is the mass of the rotor; m_p is the eccentric mass of the rotor; θ is the angle between eccentricity and axis coordinate; I is the transverse moment inertia of the rotor; I_p is the polar moment inertia of the rotor; Ω is the rotating speed; r is the radius of the rotor; L is the length between the AMB and the flexible coupling.

The stability of the AMB system by using a PD controller and a force observer compensator was verified in the research. But the force observer design is based on the dynamic equations, and there are some model uncertainties of the flexible coupling and the nonlinearities of the magnetic bearing system, the observer would not work well for all the operation speed. And the phase of estimated force signal may be lag and the amplitude may be smaller than exact disturbance.

The control structure in this paper is showed as Fig.3. A fuzzy compensated system is used to estimate the imbalance force and disturbance and the control current is modified by the output of the fuzzy compensator. The fuzzy compensated system is built on the knowledge of rotor dynamics and doesn't need a precise mathematical model. The input signals of the proposed fuzzy mechanism are obtained from the position error and velocity of the rotor and the control current of the AMB system. And making use of the concept of the fuzzy set, the compensator signals are adjustable in varies with the response.

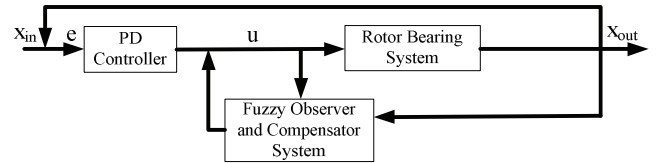


Fig.3 Control structure diagram of the single AMB system

III. DESIGN OF THE FUZZY MECHANISM

A fuzzy mechanism is constructed by the membership function and the fuzzy rules. Inputs of the fuzzy observer system proposed in this paper were established by the control current and the position of the rotor. In the fuzzy observer system, the control current and the displacement vibration signal are used to design fuzzy rules and membership functions to build up the fuzzy compensator.

The linguistic variable inputs for the fuzzy observer system are denoted as i_c and x . And the linguistic variable output is the observer force which is denoted as f . Membership functions of the input and output linguistic variables and the linguistic values for the input and output are showed as Fig.4, where the linguistic variables are labeled with "L," "M," and "S" to represent "large," "medium," and "small," respectively. The Mamdani method is used to design the membership functions of the fuzzy system. The membership bounds of the membership functions are modified from the results of the reference [5] and "try and error" results.

The fuzzy rules for the observer system are showed in table 1. There are six fuzzy linguistic values for the input linguistic variables, and three fuzzy linguistic values for the output linguistic variables. After the fuzzy observer system, the observer force is modified by a constant coefficient and feedback to the control current to make the system more stable.

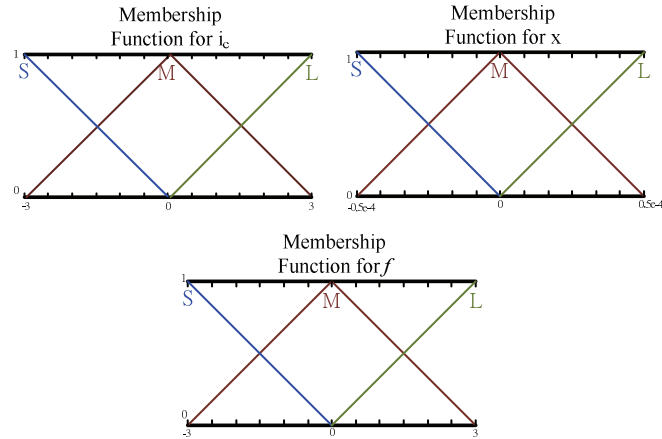


Fig.4 Membership functions of the inputs and output

Table1. Fuzzy rules

Fuzzy Rules				
		i_c		
		S	M	L
x	S	L	M	M
	M	M	M	S
	L	M	S	S

IV. SIMULATION RESULTS

The simulation program of the single AMB system is established by MATLAB. The AMB system consists by a PD controller and the fuzzy compensator as the fig.5 shows. The gain value of the PD controller and the parameters of the AMB system are shown in table 2.

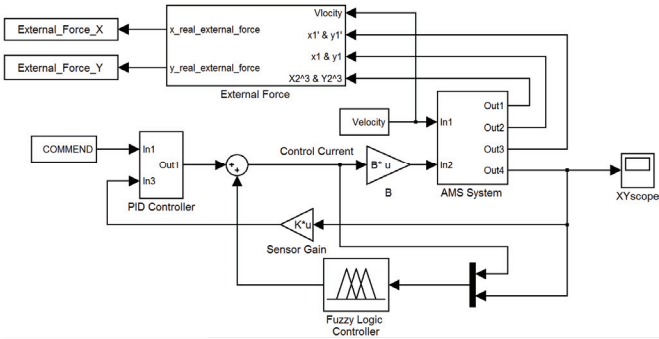
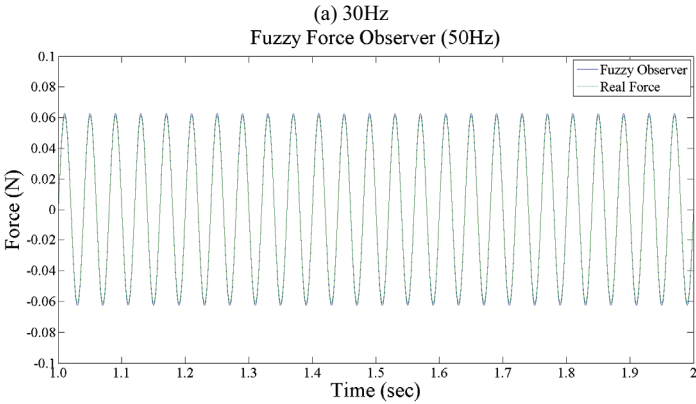
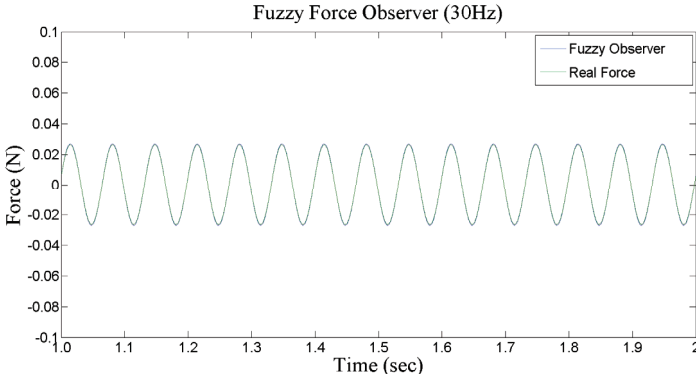


Fig.5 The AMB system established by the Simulink toolbox of the MATLAB

Table2. Parameters of the AMB system

M, the mass of the rotor	:	2.142 kg
L, length of the rotor	:	0.414 m
Mp, Eccentric mass	:	0.0013 kg
Ki, current parameter of the AMB	:	35.549
Kd, displacement parameter of the AMB	:	1.423e5
Gs, Sensor gain	:	7000V/m

From the simulation of the AMB system, the disturbance force obtained by the fuzzy observer at various rotating speeds can be showed in fig. 6. With different rotating speeds of the rotor, we can see the disturbance is displayed like a harmonic signal with different magnitude and frequency. Thus, the simulation results shows the fuzzy observer system can observers the disturbance force, and the estimated results is close to the actual disturbance force of the system, even if we can't demonstrate the system model very accurately.



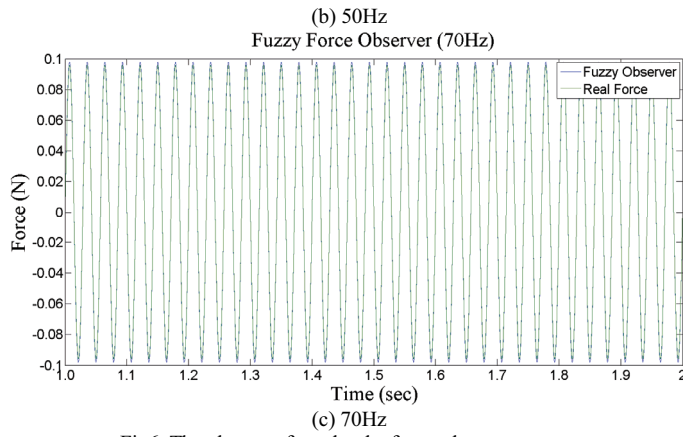


Fig6. The observer force by the fuzzy observer system

Disturbance force from fuzzy observer will sent to the AMB system to be a compensated signal which is constructed by the disturbance force. Fig.6 shows the rotating orbits of the rotor with traditional PD controller, and fig.7 is the rotating orbits with the compensated signal. The limits of both horizontal and vertical axes in PD simulations are $[100\mu\text{m} \ 100\mu\text{m}]$. The limits of both horizontal and vertical axes in simulations with fuzzy system are $[10\mu\text{m} \ 1\mu\text{m}]$. Simulation results show the fuzzy compensator can increase rotational accuracy in the operating range.

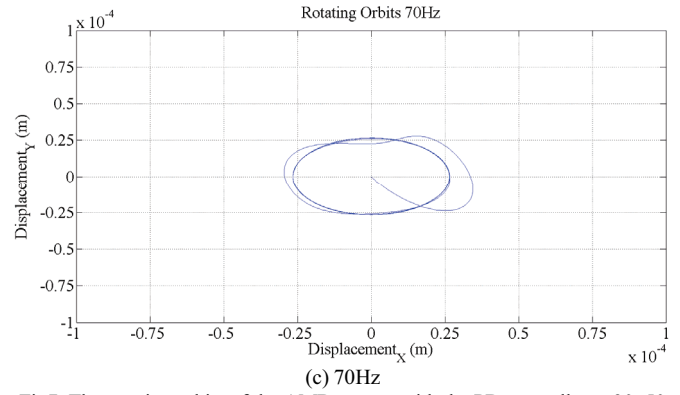
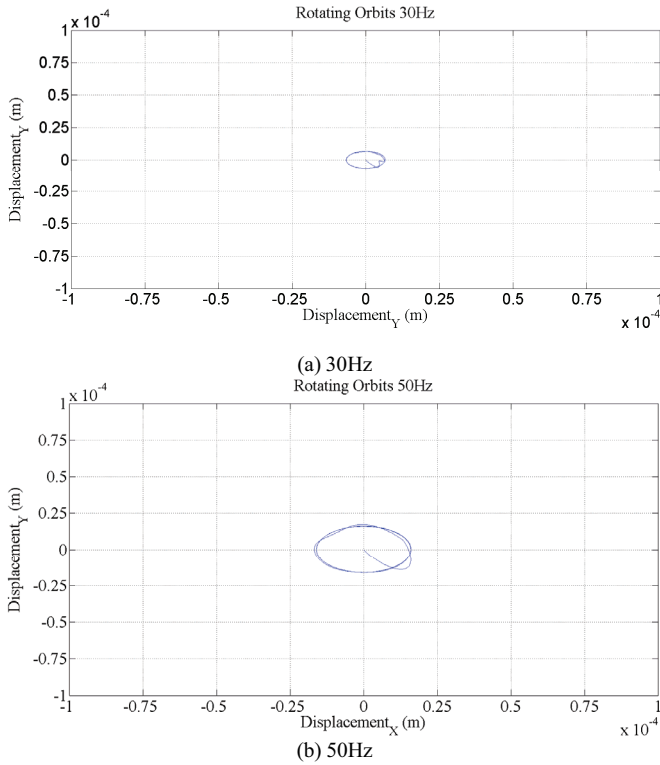


Fig7. The rotating orbits of the AMB system with the PD controller at 30, 50 and 70 Hz

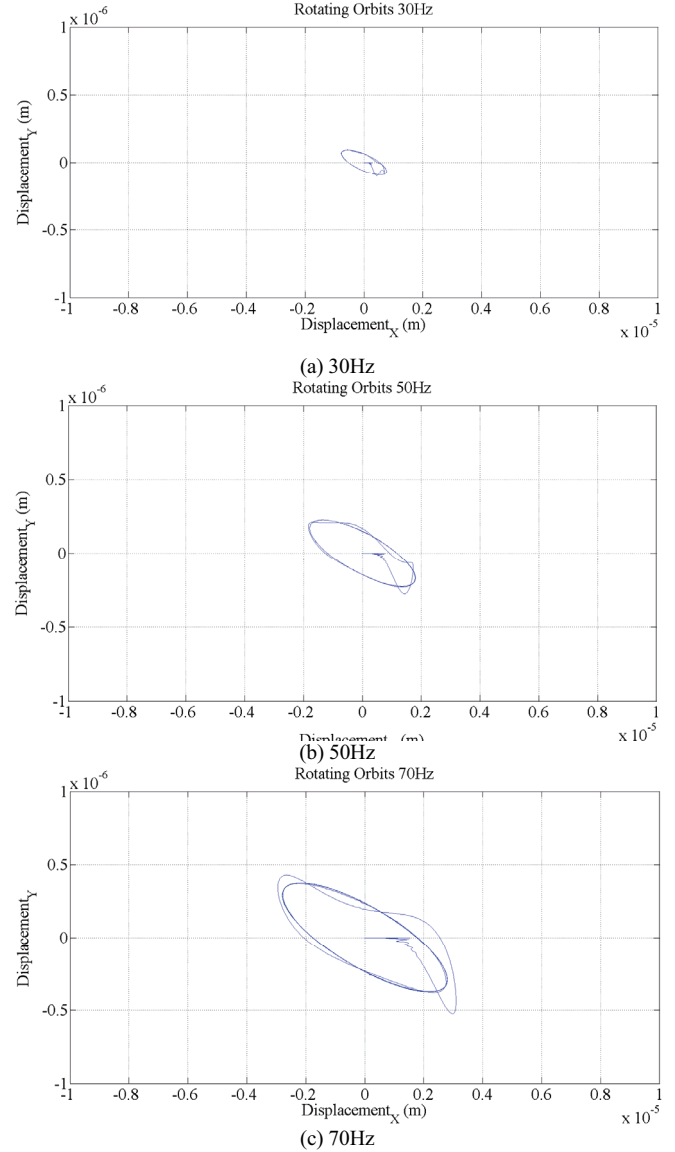


Fig8. The rotating orbits of the AMB system with the Fuzzy system at 30, 50 and 70 Hz

V. EXPERIMENT RESULTS

To validate the compensator, a single AMB system with a flexible bearing is constructed as shown in fig.9. The fuzzy

compensator is constructed in PC and is connecting with AMB system using the XPC system. The AMB system is connected to a rotor with a flexible coupling.

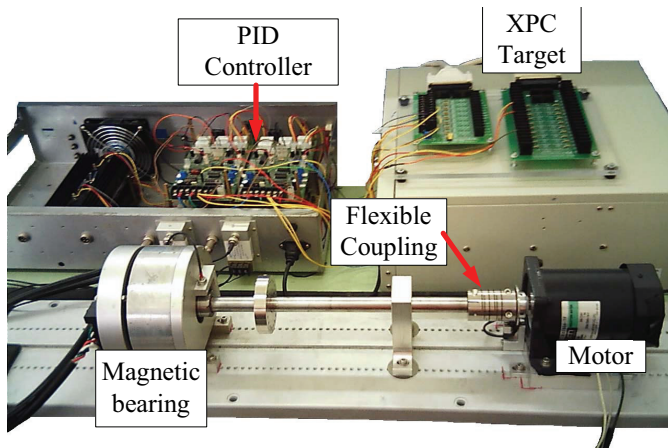


Fig9. The schematic diagram of the experiment devices

The vibrations of the shaft at the location of the AMB at several rotating speed are shown in fig.10. The rotor is controlled by a traditional PD controller with a fuzzy compensator being added to the system at 5 sec after. The blue lines in fig.10 are the average values of vibration of the shaft. The maximum peak to peak value of the vibration is approximately $5.7 \times 10^{-4} \text{ m} \sim 7 \times 10^{-4} \text{ m}$ when only using the PD controller. It demonstrates that the maximum vibration amplitude is reduced to $4.2 \times 10^{-4} \text{ m} \sim 5.3 \times 10^{-4} \text{ m}$ as the fuzzy compensator is added to the system. The average value is approximately $1.5 \times 10^{-4} \text{ m}$ when only using the PD controller and is reduced to $0.9 \times 10^{-4} \text{ m}$ as the fuzzy compensator added. It is obviously that the peak to peak values and the average values of the vibration are all suppressed after the fuzzy compensator is added. As the results, we can identify the valid of the fuzzy compensator system and it means that the fuzzy compensator system can make the system operating more smoothly, even if the system model is not accurate.

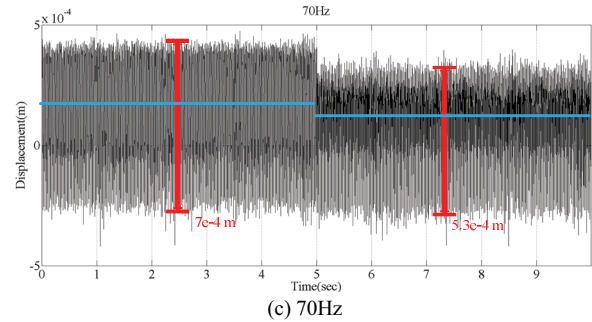
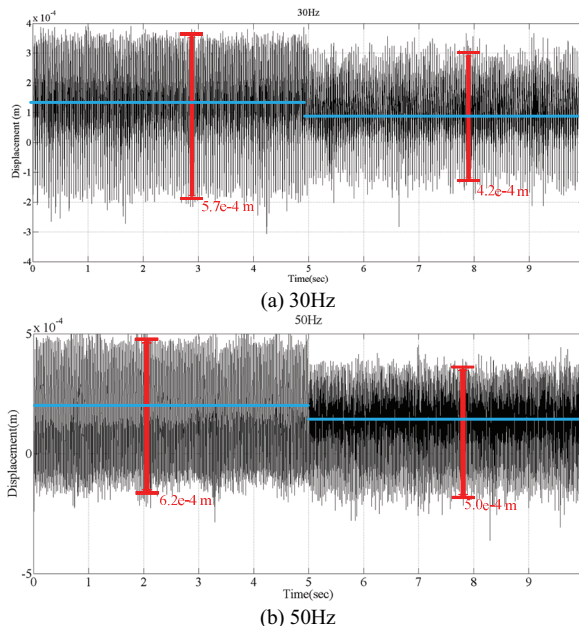


Fig.10 The experiment results of the AMB system, fuzzy observer system is utilized after 5secs.

VI. CONCLUSION

This study demonstrates that the fuzzy force compensator applied to the single AMB system is useful for restraining the unbalancing vibration and to improve the rotational accuracy. From the results of the simulation and experiment, the fuzzy observer can works well at different operating speeds. And the fuzzy observer output can feed to the AMB system to make the system operating more smoothly. The whirling orbits of the rotor in the experiment showed it can be maintained in a small range than the traditional PD controller.

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