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Digital Control of Active Magnetic Bearing Using Digital Signal Processor.

T.Shimomachi* , T.Ishimatsu* , N.Taguchi* ,S.Fukata**

* Department of Mechanical Engineering
Nagasaki University.
** Department of Mechanical Engineering
Kyushu University.

Abstruct.

Digital control laws are implemented on an active magnetic bearing system with DSP. The results of tests using a experimental apparatus are

(1)In a case that conventional PID,PIDD2 controls are employed,implemention of digital control law has similar characteristics to that of analogue control law.

(2)The experiments reveal the results that the dynamic compensation based on the observer may be better than that of the other conventional controllers.

1. Introduction

Active magnetic bearings,which suspend a rotor by the attraction of magnetic force have several advantages over mechanical and fluid bearings such as ;very low mechanical losses, very high rotation speed,wide range of operating temperature,robustness in hostile enviroment (vacuum, steam and so on),low noise and vibration,no wear,no lubrication,free from air contamination caused by lublicant.

Due to those advantages, developments of magnetic bearings have been started to use gyro and flywheel as astronautical machinery, although they have some problems such as ; high cost, low load capacity,complex composition of the bearing system.

In recent years, active magnetic bearings are commercially employed in many field where high performance is requested. Turbo molecule pump, centrifugal compressor, grinding and polishing machinery are typical examples where active magnetic bearings are adopted.

Since the magnetic bearings system are basically unstable and feedback control is indispensable to stabilize the system, conventional analogue PID controllers are frequently used. While the analogue control system enables stable operations, the digital control system is more suitable to enforce sophiscated control lows.

Generally the digital control system in active magnetic bearings has the following advantages in comparison with analogue cotrol one; generality of hardware of control system, introduction of the advanced control law, flexibility by software, possibility of realtime adjustment of control parameters by the periodic interruption .

This paper considers the digital control of an active magnetic bearing system. In order to realize a fast digital data processing, a digital signal processor (DSP:μPD77230) is introduced.

Owing to this introduction of DSP,even the advanced digital control law can be enforced with enough speed to obtain superior characteristics.

The maganetic bearing considered here is thrust magnetic bearing which is one part of 5-axis magnetic bearings system. Three types of digital controllers are designed to control the thrust magnetic bearing (horizontal, single-axis control) ;proportional-integral-derivative(PID) controller, proportional-integral-derivative-second derivative (PIDD2) controller,and a dynamic controller based on an observer.

Results of digital control were compared with those of conventional analogue control in contrability, frequency response and impulse response.

2. System Cofiguration of Thrust Active Magnetic Bearing.

Fig.1 depicts the thrust active magnetic bearing considered here. The specification of the thrust magnetic bearing is given in Talbe 1.

Table 1 The spesification of the magnetic bearing

mass of Rotor	$m=4.4$	kg
Gap length	$l_0=1.0\times10^{-3}$	m
Gain of power amp.	$b=0.5$	A/V
Bias coil current	$I_0=2.0$	A
Force constant	$K_F=240$	N/A
Time constant	$T=6.1\times10^{-3}$	s
Gap constant	$a_1=2.0\times10^3$	A/N
Gain of displacement sensor	$Ky=20.0\times10^3$	V/M
Scale factor	$\alpha=1000$	

The rotor ① and the stators ② are made of S25C. The rotor is suspended by wires in the radial direction, to be free only in the thrust direction. Position sensor ③ is eddy current type . Electromagnetic coil ④ is made of copper wire with 0.8mm diameter. Power Amplifire is transistor PWM (Pulse Width Modulation) type.

The composition of the control system is shown in Fig.2. The control signal is generated by digital controller considering the deviation of the rotor position from its base position. Then, the control signal is sent to poweramplifire to control current of electromagnets.

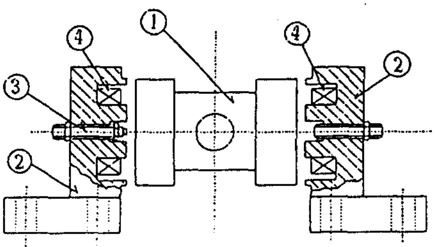

Fig. 1 Th.rust magnetic bearing

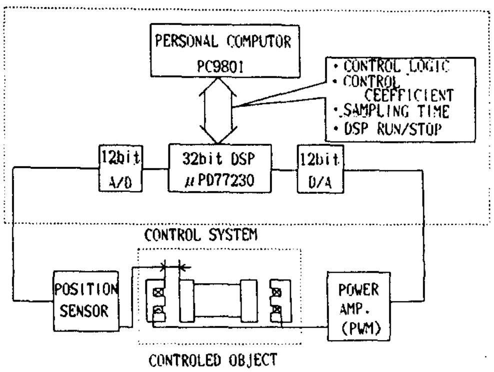

Fig. 2 System diagram

3. Dynamics of Thrust Active Magetic Bearing.

Continuous-time-system.

The linerized differential equations of thrust active magnetic bearing behavior ,describing the response of the rotor can be written as follows;

$$m\ddot{x} = K_F q \quad , \qquad (1)$$

$$T\dot{q} + q - a_1 x = bu \qquad (2)$$

where

- m : mass of rotor
- x : displacement of rotor
- K_F : coefficient of the maganetic force
- q : variable which is equal to flux in steady state
- T : time constant of flux lag
- a_1 : coefficient of gap
- b : PWM amplifire gain
- u : control input voltage

State equation of the sytsem can be rewritten as follows;

$$\dot{x} = Ax + Bu \qquad (3)$$

where

$$x=[x_1, x_2, x_3]^T=[K_\nu x, K_\nu x/\alpha, q]^T \quad ,$$

$$A=\begin{bmatrix} 0 & \alpha & 0 \\ 0 & 0 & K_F\gamma \\ \beta & 0 & -a \end{bmatrix} , \qquad (4)$$

$$B=\begin{bmatrix} 0 \\ 0 \\ ab \end{bmatrix} \qquad (5)$$

- K_ν : gain of positon sensor
- α : constant

Discrete-time system

The differential equation (3) is easily transformed into a differnce equation with a sampling time ΔT. State equation of the system in discrete-time system can be written as follow;

$$x(k+1)=\phi x(k)+hu(k) \qquad (6)$$

where

$$\phi=\exp(A\Delta T) \quad , \qquad (7)$$

$$h=\int_0^{\Delta T}\phi(t)dt\cdot B$$

4. Control law

Three types of digital control laws are employed to control the thrust magnetic bearings. In order to compare the digital control laws with the analogue control laws, all the control schemes employed are shown in the followings.

PID,PIDD2 Controller

○ Contimuous-time system.

The transfer function of PIDD2 componsator C(s) in analogue control is written as follows;

$$C(s)=K_P+\frac{1}{T_I S+1}+\frac{K_D S}{T_D S+1}+\frac{K_{D2}S^2}{(TDS+1)^2} \qquad (8)$$

and control input voltage u(s)is given as

$$U(s) = -C(s)Y(s) \qquad (9)$$

where

- K_P : Gain of proportional controller
- K_I : Gain of approximate integral controller
- K_D : Gain of approximate derivative controller
- K_{D2} : Gain of approximate second derivative controller

T_I : Time constant of integration

T_D : Time constant of differentiation

Y(s): Laplace transform of rotor desplacement

The third term in equation (8), which is added to PID controller is second derivative term in order to compensate the effect of the time lag.

○ Discrete-time system

The digital PIDD^2 control which is obtained by approximating the integration and differentiation of equation (8) by the use of Euler's method is adopted in one digital controller. Thus, the control law expressed as the sum of the following terms.

The difference equation is written as follows;

•Proportional Controller $u_P(k)$

$$u_P(k)=K_P y(k) \tag{10}$$

•approximate integral controller uI(k)

$$u_I(k)=\frac{1}{T_I+\Delta T}[T_I u_I(K-1)+\Delta T K_I y(K)] \tag{11}$$

•Appoximatae differntial controller $u_D(k)$

$$u_D(K)=\frac{1}{T_D+\Delta T}[T_D u_D(k-1)+\{y(k)-y(k-1)\}K_D] \tag{12}$$

•Approximate second differential controller $u_{D2}(k)$

$$u_{D2}(k)=\frac{1}{T_{D2}+\Delta T}[T_{D2}u_{D2}(k-1)+\{u_D(k)-u_D(k-1)\}K_{D2}] \tag{13}$$

Therefore the control input voltage u(k) is given as

$$u(k)=-(u_P(k)+u_I(k)+u_D(k)+u_{D2}(k)) \tag{14}$$

The block diagram of the PIDD2 control system is shown in Fig.3.

Observer

○ continuous-time System

One of the advantage of introducing the digital control is that a sophistcated control law can be impleted without any difficulty. Here we employed a minimal- order observer to control the thrust magnetic bearing.

The minimal-order observer is composed by the use of output y of displacement sensor as follows;

•measurable state variable $x_1=y$

•measurable state variable $x_2=[x_2\ x_3]^T$

The minimal-order observer which estimate state variable x_2 can be written as;

$$\dot{x}p=\begin{bmatrix}-\alpha l_2 & K_F\gamma \\ -\alpha l_3 & -a\end{bmatrix}\hat{x}_2+\begin{bmatrix}0\\ \beta\end{bmatrix}y+\begin{bmatrix}0\\ ab\end{bmatrix}u \tag{15}$$

where $\hat{x}_2$ is estimated value of x_2 and is given by using design parameter $L=[l_2,l_3]^T$ of obvserver as;

$$\hat{x}_2=x_p+Ly \tag{16}$$

and control input voltage U(s) is given as

$$U(s)=-(K_P+\frac{K_I}{T_I s+1})Y(s)-K_2x_2(s)-K_3x_3(s) \tag{17}$$

○ Discrete-time system

The digital control law which is obtained from the equations (15),(16),(17) by the use of Euler's method is adopted in the digital controller.

The differnce equation is written as follows;

$$x_{p2}(k)=\frac{1}{1-\Delta TA_\theta-\dfrac{\Delta T^2B_\theta C_\theta}{1-\Delta TD_\theta}}\Big[x_{p2}(k-1)+\frac{\Delta TB_\theta}{1-\Delta TD_\theta}x_{p3}(k-1)+(\frac{\Delta T^2B_\theta F_\theta}{1-\Delta TD_\theta}+\Delta TE_\theta)y(k)+\frac{\Delta T^2B_\theta G_\theta}{1-\Delta TD_\theta}u(k)\Big] \tag{18}$$

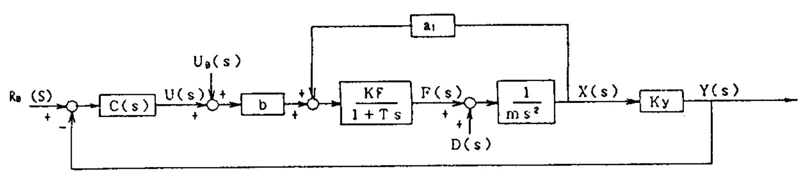

Fig. 3 Block diagram of the PIDD2

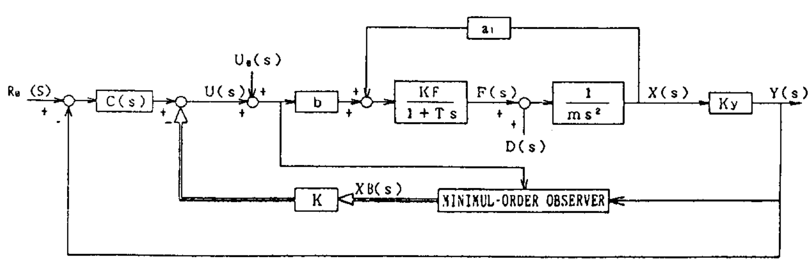

Fig. 4 Block diagram of the observer

$$x_{p3}(k)=\frac{1}{1-\Delta TD_\theta-\dfrac{\Delta T^2B_\theta C_\theta}{1-\Delta TA_\theta}}\Bigg[x_{p3}(k-1)$$

$$+\frac{\Delta TC_\theta}{1-\Delta TA_\theta}x_{p2}(k-1)+(\frac{\Delta T^2C_\theta E_\theta}{1-\Delta TA_\theta}+\Delta TF_\theta)y(k)$$

$$+\Delta TG_\theta u(k)\Bigg], \quad (19)$$

$$\hat{x}_2(k)=x_{p2}(k)+l_2y(k), \quad (20)$$

$$\hat{x}_3(k)=x_{p3}(k)+l_3y(k) \quad (21)$$

and control input voltage is given as

$$u(k)=-(u_p(k)+u_i(k)+u_2(k)+u_3(k)) \quad (22)$$

where

$$u_p(k)=k_py(k), \quad (23)$$

$$u_i(K)=\frac{1}{T_i+\Delta T}[T_iu_i(k-1)+\Delta TK_iy(k)], \quad (24)$$

$$u_2(k)=K_2x_2(k), \quad (25)$$

$$u_3(k)=k_3x_3(k), \quad (26)$$

$$A_\theta=-\alpha l_2, \quad E_\theta=-\alpha l_2+K_p\gamma l_3$$

$$B_\theta=K_F\gamma, \quad F_\theta=-\alpha l_2l_3-al_3+\beta \quad (27)$$

$$C_\theta=-\alpha l_3, \quad G_\theta=ab$$

$$D_\theta=-a$$

The block diagram of the observer control system is shown in Fig.4.

5. Experimental Results

The parameters of PID controller were adjusted hammering on the end of rotor so that impulse response have the favorable damping shape, and second derivation parameter was adjusted unless that the noise caused by this parameter gives any effects on the control system. Parameters of the controller are shown in Table.2. The sampling freqUency of digital control system PIDD2 and observer are 38.5kHz,24.8kHz respectively.

(1)Frequency Respose

The fequency responses of each controllers are shown in Fig.5, Fig.6, Fig.7 . The frequency responses were measured as the ratio of input disterbance $U_\theta(s)$ and resultant output disturbance U(s)(see Fig.3,Fig.4).

As we expected almost the same performance of digital control in comparison with analogue control was obtained in

Table 2 Parameters of controller(Analogue/Digital)

	PID	PIDD2	OBSERVER
K_I	3.6/2.5	3.6/2.5	100
K_P	0.39/0.35	0.39/0.35	27
$K_D\times10^{-3}$	3.4/3.8	3.4/3.8	–
K_2	–	–	65
K_3	–	–	6
T_I	0.48/0.48	0.48/0.48	2.2
$T_D\times10^{-4}$	3.3/3.3	3.3/3.3	–
T_{D2}	3.3/3.3	3.3/3.3	–
(l_2,l_3)	–	–	(0.4 ,0)

frequency response test.

It should be noted that the dynamic controller based on an observer had better controllability on follow-up performance.

(2) Impulse Response

The impulse response of each controller are shown in Fig.8, Fig.9, Fig.10.Impulse responses were measured by hammering on the end of rotor so that the maximum displacement of rotor became be 100 μm.

(3) Steady state variation of rotor displacement

Experimental results of rotor displacement are shown in table 3. Digital controller of PIDD2 and observer have little variation of displacement and observer have the noise problem less than the other controller.

Steady state variation of rotor displacement characteristic was not satisfactry, because rotor displacement singal from the displacement sensor was influenced by the noise of PWM Amplifire.

Table 3 Steady state variation of rotor displacement

	PID	PIDD2	OBSERVER
ANALOGUE	2.4μm	2.6μm	–
DIGITAL	2.5μm	2.0μm	2.0μm

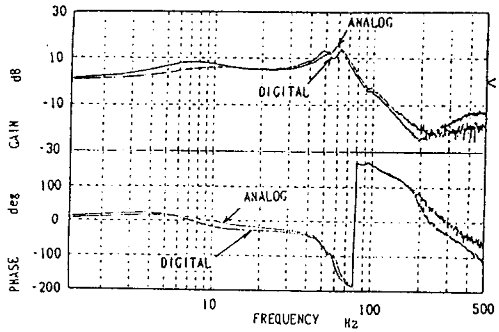

Fig. 5 Frequency responce of PID

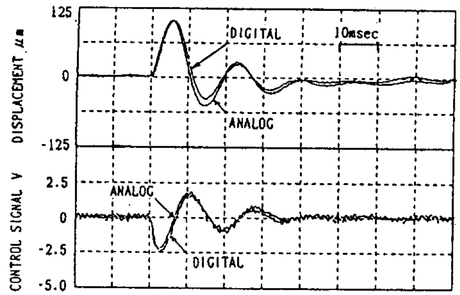

Fig. 8 Impulse responce of PID

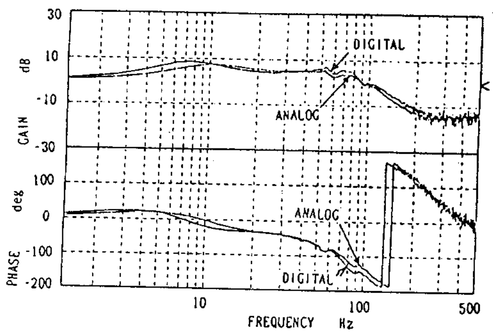

Fig. 6 Frequency responce of PIDD2

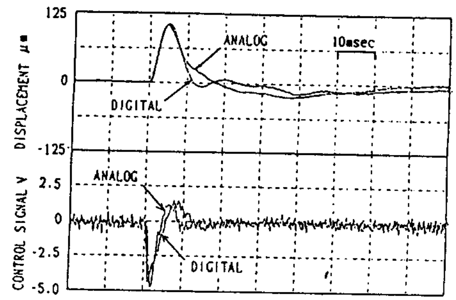

Fig. 9 Impulse responce of PIDD2

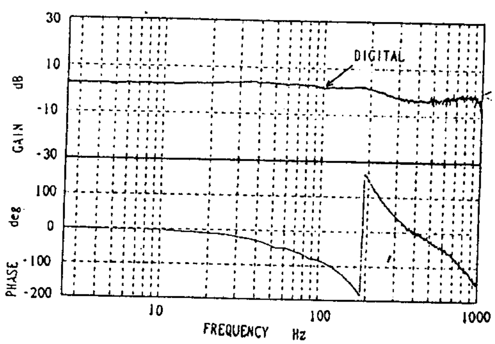

Fig. 7 Frequency responce of observer

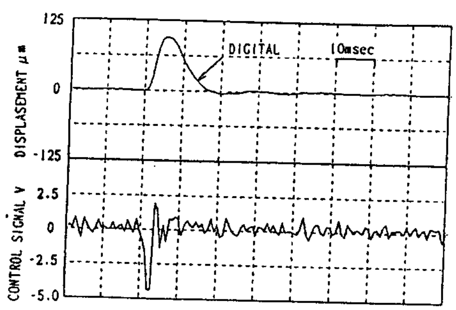

Fig.10 Impulse responce of observer

6. Conclusion

Digital control laws are implemented on an active magnetic bearing system with DSP. The results of tests using an expermental apparatus are shown in the followings.

(1) In a case that conventional PID, PIDD2 control are employed, implementation of digital control law has similar characteristics to that of analogue control law.
This means that DSP is fast enough to execute a tactful control law.

(2) The experiments reveal the result that the dynamic compensation based on the observer may be better than that of the other conventional controllers.

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