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Research Article

Studies on Control Aspects of Active Magnetic Bearings

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Abstract

The Active Magnetic Bearing (AMB) ensures complete levitation of journal from bearing obviating friction and wear thereby reducing the maintenance cost. In the AMB system the journal (rotor) is held in the desired position relative to the bearing (stator) by electromagnetic control. The Proportional-Integral-Derivative (PID) control is the most common control method. The values of K_P, K_D and K_I that governs the PID controller are determined using trial and error methods. In many cases the method of their determination is not explicitly described. In the present research work, a control method based on voltage control is proposed and implemented. The simplicity and accuracy of the method is demonstrated by the experimental validation.

Keywords: *PD, PID, Controller tuning, Adaptive Controller, Friction, Wear.*

1. Introduction

The contact between the two surfaces during relative motion is generally avoided so as to eliminate friction and wear, however in several applications the load and speed conditions are not favorable and the tribo pair operates in mixed lubrication regime (S M Muzakkir *et al*. 2011; S M Muzakkir *et al*. 2010). Many alternative technologies have been employed to separate the contacting surfaces (S.M. Muzakkir, *et al* 2014; Samanta and Hirani 2008; Samanta, P Hirani 2007; Hirani *et al* 2001; Lijesh and Hirani 2015a; Shankar, Sandeep, and Hirani 2006; Chittlangia *et al*. 2014; Lijesh and Hirani 2015b; S M Muzakkir and Hirani 2015a; S M Muzakkir, Hirani, and Thakre 2015), however the use of Multi-Walled Carbon Nano-tubes (MWCNT) (Popov 2004; Lijesh, Muzakkir, and Hirani 2015), that has recently emerged as an antiwear additive, is being accepted as one of the most effective solution. Other anti-wear additives like Zinc (S. M. Muzakkir, Hirani, and Thakre 2013), molybdenum disulphide nano-particles (S M Muzakkir and Hirani 2014; S M Muzakkir and Hirani 2015b; S M Muzakkir and Hirani 2015c; S M Muzakkir and Hirani 2015d) Tungsten Disulphide etc are also being used in lubricants for minimizing wear.

The active magnetic bearings have many advantages over conventional bearings, the main being complete levitation of journal from bearing (contactless operation) obviating friction and wear. Therefore lubrication is also not required. This reduces maintenance cost. In the Active Magnetic Bearing (AMB) system the journal (rotor) is held in the desired position relative to the bearing (stator) by electromagnetic control. The proximity sensors monitor the position of the journal continuously. The microprocessor based controller generates a signal based on the journal position. The generated signal is amplified and corresponding electric currents are induced in the windings of the electromagnets of the stator. The magnetic forces thus produced serves to restore the journal to the desired position so that stable centering is achieved. The principle of operation of AMB is shown in Fig 1.

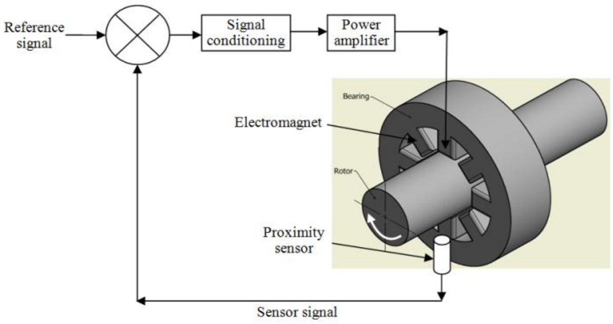

Figure 1 Principle of Active Magnetic Bearing

The design of AMB requires the integration of electromagnets (actuators), proximity sensors and measured values of physical variables. This requires a controller and a suitable algorithm to achieve the desired performance. Different design approaches have been proposed with reference to the controller design,

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*Corresponding author: **S. M. Muzakkir** sensing techniques, eddy current effects etc. [Agarwal and Chand 2009, Chen *et al* 2009, Morita *et al* 2009, Cade *et al* 2009, Sun *et al* 2009]. The main purpose of the magnetic bearing control loop is to stabilize the rotor motion about a set point, usually its center of rotation. Therefore, the controller must generate a restoring force with sufficient damping to minimize rotor oscillations about the center of rotation. Many methods of controlling the AMB are being used at present; they include Proportional-Derivative (PD), Proportional-Integral-Derivative (PID), Q-parameterisation [Mohamed and Busch-Vishniac, 1995], **μ** synthesis [Nonami and Ito, 1996], adaptive control [Lun and Coppola, 1996], H∞ control [Shiau and Sheu, 1997], LMI Control [Hong and Langari, 1997], neural network control [Komori and Kumamoto 1998], and hybrid neural fuzzy control [Hajjaji and Ouladsine, 2001]. The schematic diagram of the AMB is shown in figure 2.

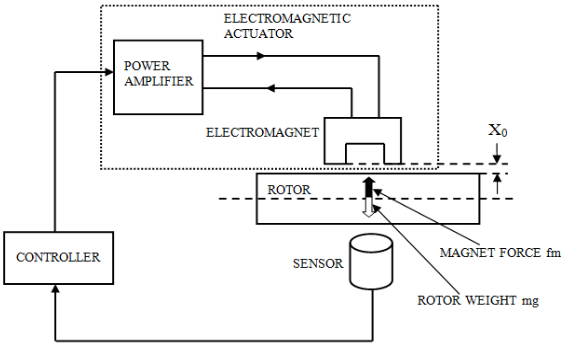


Figure 2 Schematic diagram of Active Magnetic Bearing with control loop [Gerhard Schweitzer and Eric H. Maslen, 2009]

The most common control law used for generating the current command signal is expressed as a function of the displacement x.

$$i(x) = -\frac{(k-k_s)x + d\dot{x}}{k_i} \tag{1}$$

This control law, known as PD control, has two feedback parts, a proportional feedback with control parameter P and a differential feedback with control parameter D. Schematic of PD control is shown in figure 3.

$$P = \frac{k-k_s}{k_i} \tag{2}$$

$$D = \frac{d}{k_i} \tag{3}$$

In the PD control, the proportional feedback is similar to mechanical stiffness and the differential feedback coefficient is similar to mechanical damping.

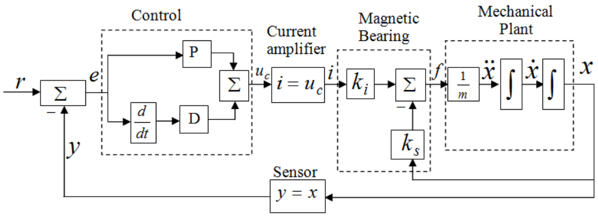


Figure 3 Active magnetic bearing PD control loop [Gerhard Schweitzer and Eric H. Maslen, 2009]

The external load (denoted by Δf_e) will change the rotor position (denoted by x), which is then adjusted by the use of reference command input signal r; and control parameters P and D. These parameters (i.e. P, D) depend on stiffness k and damping d of the closed-loop system. The value of k_s is dependent on the length of the magnet gap, s_0, and on the current operating point, i_0. The magnet gap is dependent upon the manufacturing uncertainties and is also affected by differential thermal growth between the rotor and stator and by centrifugal growth of the rotor. Since k_s depends on $s^3{}_o$, even relatively small changes in s_o produce relatively large changes in k_s. Further, the current operating point, i_0, depends on the static load carried by the bearing: small changes in static load can lead to significant changes in k_s. All these considerations cause an uncertainty on the order of 20% [Gerhard Schweitzer and Eric H. Maslen, 2009] in value of k_s.

The value of damping d is dependent on the stiffness. The aim of the designer is to use a critical damping value for eliminating the oscillations of the rotor. The damping values between 0 and 2√mk (which corresponds to 50% of the damping ratio) are generally preferred [Gerhard Schweitzer and Eric H. Maslen, 2009]. If the damping is low, the rotor oscillations will become prominent resulting in unstable behavior.

The change in the operating point, denoted by Δx, for an external load Δf_e corresponding to the reference command input signal r is expressed as:

$$\Delta x = \frac{k-k_s}{k} r \tag{4}$$

This equation (4) indicates that in PD control the deviation in rotor position (Δx) does not follow the reference command r exactly. This is considered as the main limitation of PD control. Moreover, there is a sharp rise in the stiffness to static load change when adding an integral (I) term. This limitation is overcome by the use of PID control as shown in figure 4.

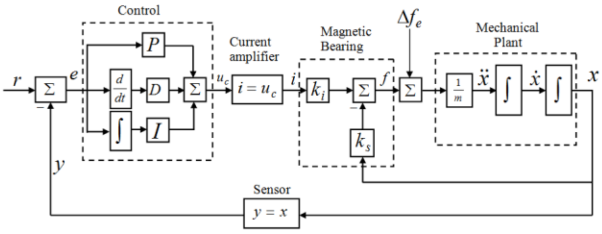


Figure 4 Active magnetic bearing PID control loop [Gerhard Schweitzer and Eric H. Maslen, 2009]

In PID control, all the signals within the control loop remain constant for a given constant static load. This means that the error signal remains zero under a constant static load. For the accurate control of the rotor position, the PID control must be able to maintain the rotor position at the set point irrespective of the external load. However, it will require a bearing with an infinite static stiffness. In order to sustain accurate performance of the closed loop system, the integrating feedback gain I must not be large because the integrating feedback produces a controller phase lag that counteracts the phase lead of the velocity feedback. In AMB, with very heavy external load, the rotor position is kept constant by maintain y = x = r. If the external force exceeds this limit, the rotor displacement will suddenly become equal to the air gap causing contact between the rotor and stator. The main limitation of AMB is that it does not provide any overload capability in contrast to other bearings, therefore, the load capacity of AMB is kept much higher that the expected external load.

Most of these values of K_P, K_D and K_I that governs the PID controller are determined using trial and error methods. In many cases the method of their determination is not mentioned. However, a systematic approach of determination of K_P, K_D and K_I was proposed, but it was based on current control and requires all system properties. The data acquisition rate and data analysis plays a significant role in the control of the rotor and is thus prone to experimental errors.

In the present research work, a control method based on voltage control is proposed and implemented. This method is used for the determination of K_P, K_D and K_I. The simplicity and accuracy of the method is demonstrated by the experimental validation.

2. Design of AMB Control System

The design of control system consists of four distinct steps. In the first step, the system to be controlled is modeled in form of differential equations based on the physics governing the system. The system information may be obtained by measuring the system response after a known input signal is given to the system. A transfer function is then created for the system to be controlled. In the second step, a suitable controller (PD or PID: depending upon the system characteristics) is designed. In the third step, performance and stability of the controlled system are evaluated and design changes are incorporated until the controller that satisfies the design requirement is obtained. Finally in the fourth step, the performance of the controller is evaluated on the actual system.

In the previous work [Kumar *et al*, 2014], current controller was used in which it has been assumed that magnetic bearing current instantly follows the command current from the power amplifier input. This is based on the law of linearized bearing force which expresses the force as a function of current. However, the inductance of the magnetic bearing coil will resist any sudden change in the current. Therefore, fast current change can only be achieved by a suitable high internal power amplifier. Since the current amplifier cannot control the addition system dynamic introduced by the coil inductance, therefore voltage amplifiers are preferred.

It may thus be concluded that the AMB controller must incorporate the electrical properties of the bearing magnets as well as amplifier i.e. the coil inductance (L), resistance (R) and the amplifier voltage (V). Moreover, the rotor motion in the magnetic field of the bearing also generates a voltage across the bearing coil, similar to the case of motor (this induced voltage is proportional to the speed of the rotor). Therefore, the total voltage of the power amplifier is used to overcome the coil inductance, coil resistance and motion induced voltage (k_V) as shown in figure 5.

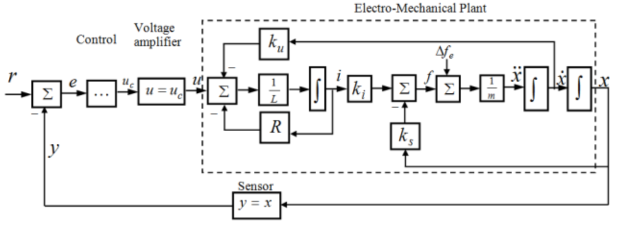


Figure 5 Voltage controlled linearized PID controller [Gerhard Schweitzer and Eric H. Maslen, 2009]

The total voltage generated by the voltage amplifier is given in equation (4):

$$V = Ri + L\frac{di}{dt} + k_V \frac{dx}{dt} \tag{4}$$

The amplifier has to compensate for the losses occurring due to eddy current, flux leakage, magnetic hysteresis and other sources. It is thus inferred that the coil winding voltage (V) is the true system input variable rather than the coil current (i). It will thus be better to implement voltage to voltage amplifier. There are several other advantages of employing the voltage control as compared to current control. It provides higher overall system robustness since the plant model is more accurate, (especially in the presence of dynamics limitations e.g. due to a low DC bus voltage or due to power amplifier bandwidth limitations), weaker open-loop instability (no eigen value in right half of the complex plane), very low stiffness values easier to implement, simpler power amplifier architecture (no underlying current control loop), possibility to benefit from the two-way property of electromechanical transducer.

The major disadvantage of the system with voltage control is the existence of one extra pole due the inclusion of inductance term and the control parameters can no more be readily interpreted by analogy of mechanical spring damper system as in the case of current control. This is the reason for which the current control is used in many industries. Above to these disadvantages voltage control are highly robust, accurate, weaker open loop stability and low stiffness values makes it easier to implement.

Considering the advantages of the voltage control in the present work experiments were performed using PID controller with voltage to voltage amplifying system. The main objective of the present work is to implement a voltage controller to statically levitate the shaft. For this an experimental setup was been developed and the detailed description of the test setup has been provided in [Lijesh and Hirani, 2015]. For the developing the controller in the present work high speed voltage input and output system with frequency of 1MHz from National Instrument was purchased and the voltage is amplified using the voltage amplifier with an amplifying rate of 1V/10μs as shown in figure 6. The proximity sensor is capable of measuring the displacement of shaft at a frequency of 100kHz.

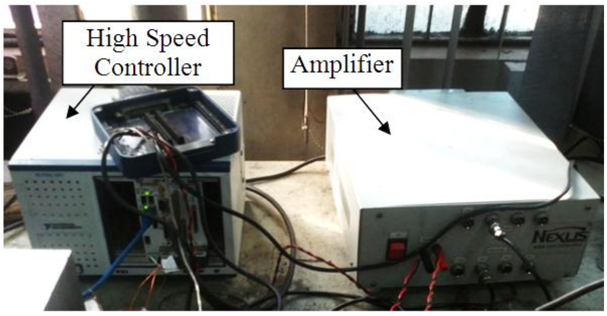


Figure 6 High Speed controller and amplifier

The PID controller has been designed using LABVIEW software as shown in figure 7.

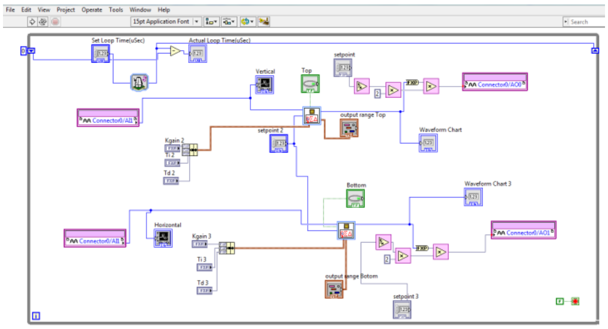
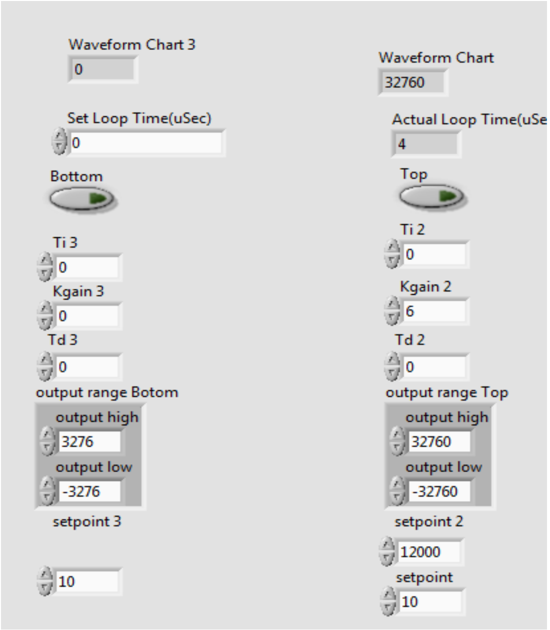


Figure 7 LABVIEW coding for PID control

Based on the input signal from the proximity sensor the output voltage is decided by the PID controller. In the present work the value of K_p, K_i and K_d is decided by trial and error method. It was observed that due to the voltage controller the system was easily controllable using only K_p value and it was not required to input K_d and K_i for static levitation.

3. Experimental results and discussion

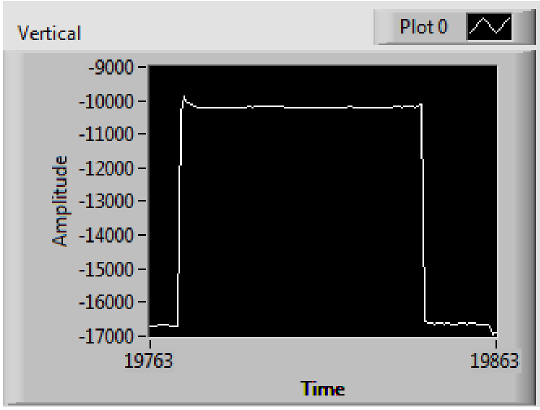
The inputs to the AMB are shown in figure 8(a) and the top and bottom position of the rotor is shown in figure 8(b). After in putting K_p value the levitated position of the rotor is shown in figure 8(c).



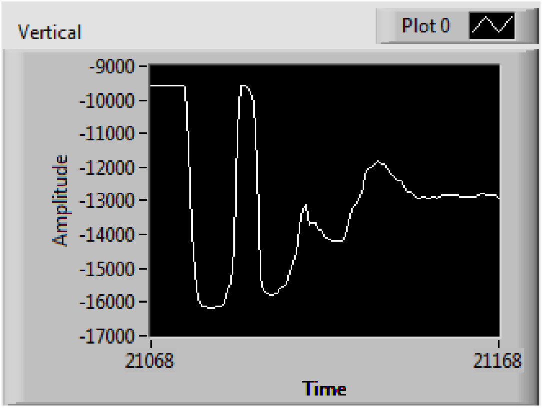
Waveform Chart 3
0
Set Loop Time(uSec)
0
Bottom
Ti 3
0
Kgain 3
0
Td 3
0
output range Botom
output high
3276
output low
-3276
setpoint 3
10

Waveform Chart
32760
Actual Loop Time(uSe
4
Top
Ti 2
0
Kgain 2
6
Td 2
0
output range Top
output high
32760
output low
-32760
setpoint 2
12000
setpoint
10

(a) Input to the controller



(b) Position of rotor at the bottom and top of electromagnet



(c)Rotor in levitated position

Figure 8 Input and output of AMB

Conclusions

A Proportional-Integral-Derivative (PID) control method based on voltage control is proposed and implemented. The PID controller has been designed using LABVIEW software. The rotor was shown experimentally to be levitated under a given static load. Due to the voltage control method, the system was easily controllable using only K_p value and it was not required to input K_d and K_i for static levitation.

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