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Research Article

Hybrid ILC Strategy for Magnetic Ball Suspension System

[1]S. Sathiyavathi, [1]K. Krishnamurthy, [2]P.K. Bhaba and [3]S. Somasundaram
[1]Department of Mechatronics Engineering, Kongu Engineering College, Erode, India
[2]Department of Chemical Engineering,
[3]Department of Instrumentation Engineering, Annamalai University, Annamalai Nagar, India

Abstract: Controlling of magnetic ball suspension system using hybrid Iterative Learning Controller (ILC) is investigated in this study. Hybrid ILC modifies the control input for the next iteration by learning from the present input and the errors of previous iteration without reconfiguration of the existing Proportional, Integral and Derivative (PID) controller. Firstly, hybrid ILC is employed to stabilize the ball and then set point tracking is performed to evaluate the efficacy of the controller. The effectiveness of designed hybrid ILC is analyzed based on performance indices via simulation.

Keywords: Compensator, hybrid ILC, magnetic ball suspension system, PID controller

INTRODUCTION

Despite many sophisticated control theories and techniques that have been proposed, PID controllers continue to be the most commonly used controller in the industrial processes. The reason is that these controllers have a simple structure and can be easily implemented (O'Dwyer, 2006; Visioli, 2004; Ming *et al*., 2002).

The PID controllers give reasonable performance if the repeatable task is simple. At the same time if the reference trajectory contains high frequency components, then it is difficult to achieve accurate tracking using standard PID controller. One solution to this problem is to incorporate the repetition property by adding a learning component to the PID controller. By doing so, the loop is called as Iterative Learning Controller (ILC). Wang *et al*. (2013) proposed a combination of PI and ILC based on two dimensional Rosser's system to achieve monotonic convergence. Liu *et al*. (2010) proposed an ILC scheme based on the Internal Model Control. Tayebi *et al*. (2008) developed robust iterative learning control based on the youla parameterization approach to obtain the robust control. Xu *et al*. (2004) presented the various configurations of ILC schemes and the corresponding convergence condition for each configuration.

The ILC design mentioned in the references above are difficult to design and it requires modifying the existing PID loop. In this study, a new hybrid ILC strategy is proposed. The proposed strategy does not require reconfiguration of PID controller.

To prove the effectiveness of the proposed hybrid ILC, the magnetic ball suspension system is taken as an example. Magnetic ball suspension system is a nonlinear and unstable system, thus provides a challenge to the control engineers and researchers. Magnetic levitation is used in wide range of applications such as maglev train, magnetic bearings, wind tunnel, vibration isolation and conveyor systems, etc. The reason for increasing popularity is that there is no mechanical contact, friction and noise, component wear, vibration, maintenance cost, etc., in which high precision positioning is achieved (Lee *et al*., 2000).

The task of the Magnetic Ball Suspension System like experiment is to bring the ball from any initial position with any initial speed to a desired position on the air by applying an appropriate current to the electromagnet. Thus, the proposed Hybrid ILC strategy that provides precise positioning of ball in magnetic ball suspension system will provide a solution to wide number of applications.

MATERIALS

Figure 1 shows the schematic illustration of magnetic ball suspension system. The magnetic Force (F) produced by the electromagnet is opposite to gravity force (mg) and it maintains the suspended steel ball in a levitated position. The magnetic force depends on the electromagnet current (i) and the air gap (x) between the steel ball and the electromagnet.

The motion of the steel ball in the magnetic field is expressed as (Ahmed and Ouladsine, 2001):

$$m\ddot{x} = mg - c\frac{i^2}{x^2} \tag{1}$$

Corresponding Author: S. Sathiyavathi, Department of Mechatronics Engineering, Kongu Engineering College, Erode, India

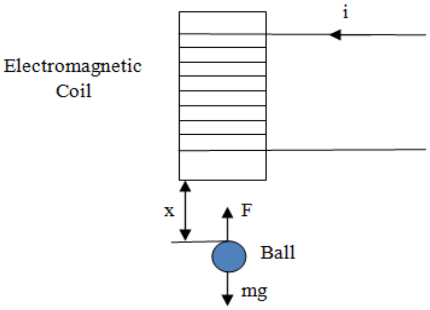

Fig. 1: Schematic illustration of an electromagnetic ball levitation system

Table 1: Parameters of magnetic ball suspension system

Parameters	Description	Value
m	Mass of the ball (kg)	0.533
x_0	Nominal air gap (cm)	0.950
i_0	Equilibrium current (A)	1.280
g	Gravitational acceleration (m/s^2)	9.800
c	Magnetic constant (Nm^2/A^2)	37.75*10^{-5}

On linearizing the Eq. (1), the transfer function is obtained as:

$$\frac{X(s)}{I(s)} = \frac{-c\left(\frac{2i_0}{x_0^2}\right)}{ms^2 - c\left(\frac{2i_0^2}{x_0^3}\right)} \tag{2}$$

Table 1 summarizes the parameters used in the magnetic ball suspension system (Lin and Tho, 1998). The operating range of the system is 0.95-1.25 cm.

Based on the system parameters, the transfer function of the plant is obtained as:

$$G_p(s) = \frac{X(s)}{I(s)} = \frac{-2.009}{s^2 - 2.7068} \tag{3}$$

The above plant transfer function shows that magnetic ball suspension system is second order unstable system.

METHODOLOGY

The structure of hybrid ILC is shown in Fig. 2. The ILC block is cascaded to the existing PID controller. The proposed hybrid ILC structure uses the modified reference signal (y_d) and the actual output of previous cycle (y_i) to generate the new reference signal ($y_{d,i+1}$) for the PID controller. Here, i denotes the current iteration. G_p (s) is the plant model and G_{ff} (s) is the feed forward compensator. The compensator G_{ft} (s) is used to provide phase compensation which increases linearly with frequency. The compensator G_{ft} (s) is defined as:

$$G_{ft}(s) = \frac{a}{s+a} \tag{4}$$

The filter parameter ‘a’ is computed as 1.1 rad/sec based on bode response of the system. The PID controller gains K_p, K_i and K_d are calculated as -23.591, -22.93 and -5.87 based on the tuning method proposed by Rotstein and Lewin (1991).

RESULTS AND DISCUSSION

To evaluate the performance of the proposed controller, the simulation is carried out for the set point tracking of 50% of operating point (1.1 cm). The performance of proposed controller is analyzed based on time domain specifications such as rise time, settling time, overshoot, ISE and IAE. The servo response of the proposed controller at the operating point of 1.1 cm (50% of operating point) is recorded in Fig. 3. The time domain performance measures are calculated and tabulated in Table 2.

From Table 2, it is clear that the proposed hybrid ILC yield a fair transient response with no overshoot. The Integral Square Error (ISE) and Integral Absolute Error (IAE) are also less.

The next objective is to test its robustness. The controller should be able to react to change in the set points. The robustness test of the proposed hybrid ILC is investigated for the set point tracking of ±5 and ±10% at the operating point of 1.025 cm (25% of operating point) as the ball position and 1.175 cm (75% of operating point) as the ball position.

Closed loop simulated transient responses of hybrid ILC for the set point tracking of ±5 and ±10% at the operating point of ball position as 1.025 cm are recorded in Fig. 4. The performance measures are tabulated in Table 3.

The robustness test for the proposed hybrid ILC for the set point tracking of ±5 and ±10% at the operating

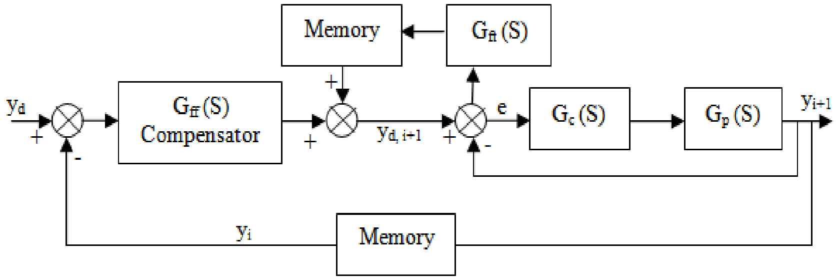

Fig. 2: Structure of hybrid ILC

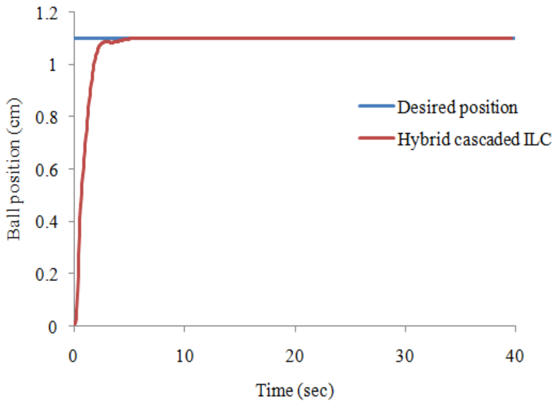

Fig. 3: Servo response of proposed hybrid ILC at the operating point of 1.1 cm

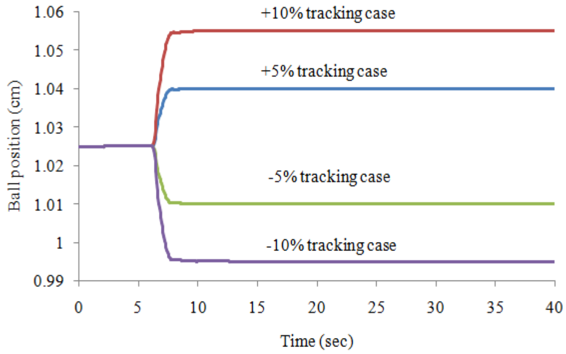

Fig. 4: Tracking case of proposed hybrid ILC at the operating point of 1.025 cm

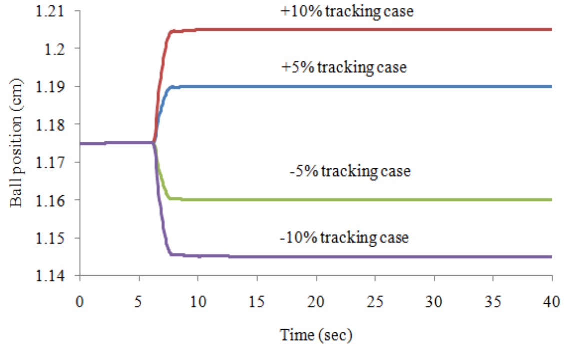

Fig. 5: Tracking case of proposed hybrid ILC at the operating point of 1.075 cm

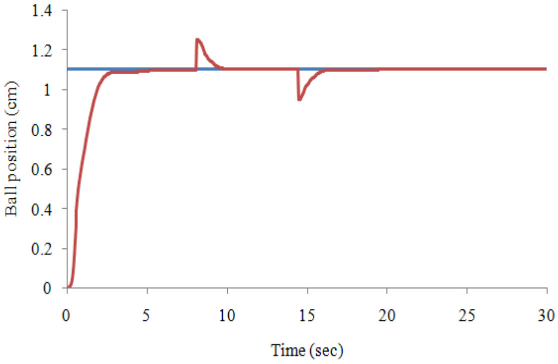

Fig. 6: Response of proposed hybrid ILC for disturbance rejection test at the operating point of 1.1 cm

Table 2: Performance measure of proposed hybrid ILC at the operating point of 1.1 cm

Controller	Overshoot (%)	Settling time (sec)	ISE	IAE
Hybrid ILC	0	5.58	12.18	17.56

Table 3: Performance measures of proposed hybrid ILC at the operating point of 1.025 cm

	Proposed hybrid ILC			
Performance measures	+5%	-5%	+10%	-10%
Overshoot (%)	0.0000	0.0000	0.0000	0.0000
Settling time (sec)	7.9200	7.9000	8.0000	8.1000
ISE	0.0249	0.0247	0.0996	0.0991
IAE	1.7196	1.7115	3.4386	3.4305

Table 4: Performance measures of proposed hybrid ILC at the operating point of 1.075 cm

	Proposed hybrid ILC			
Performance measures	+5%	-5%	+10%	-10%
Overshoot (%)	0.0000	0.0000	0.0000	0.0000
Settling time (sec)	7.9200	7.8000	8.0400	8.1600
ISE	0.0249	0.0247	0.0997	0.0991
IAE	1.7203	1.7111	3.4402	3.4301

point of ball position as 1.175 cm are recorded in Fig. 5. The performance measures are tabulated in Table 4.

The results clearly indicate the superiority of the proposed controller having no overshoot and less settling time. From the responses, it is proved that the proposed controller continually adapt the changes in the set point to maintain the consisted performance reasonably.

The aim of disturbance rejection test is to observe the response of the proposed hybrid ILC when a load disturbance occurs. The expected response from the proposed controller is an immediate and appropriate control action to maintain the ball position at the desired set point regardless of the changes in the position of the ball. The disturbance is given at 7 and 14 sec. The controller response to sudden change in the set point and return to the desired set point after the disturbance is removed. The simulation is carried out successfully and the result is shown in Fig. 6.

The response in Fig. 6 shows that the proposed controller takes immediate and appropriate control action to maintain the ball position at the desired set point regardless of the changes in the position of the ball.

Since the system transfer function is known, frequency response analysis is done with Nyquist plot. The unit circle is drawn for the nyquist plot. As seen in Fig. 7, the system works properly for frequencies less than 22.1 rad/sec.

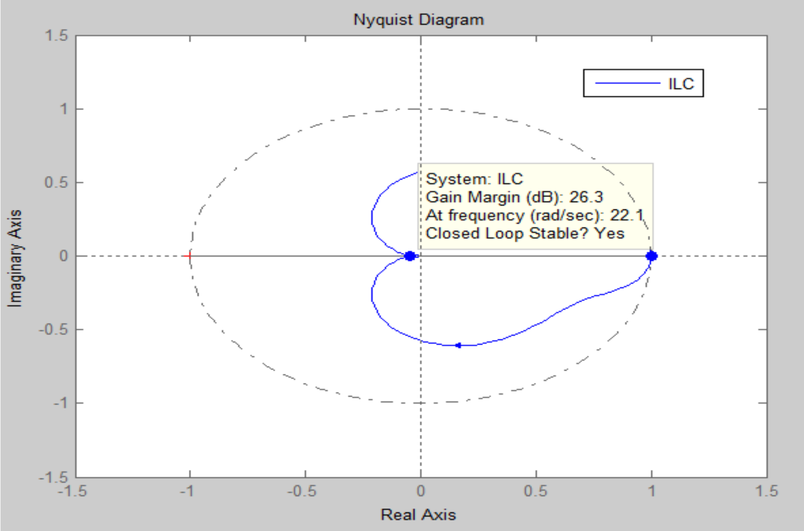

Fig. 7: Nyquist diagram for stability analysis

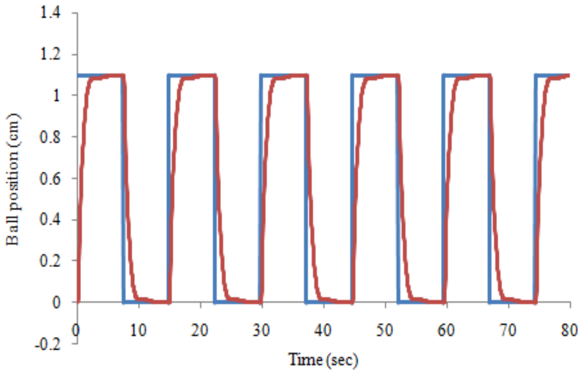

Fig. 8: Square wave tracking of proposed hybrid ILC

Figure 8 shows the tracking results of a desired square wave trajectory. Small errors are observed when the ball changes its direction. From Fig. 8, it is concluded that for small frequencies proposed controller gives better performance.

CONCLUSION

In this study, the hybrid ILC (iterative Learning Controller) is designed for magnetic ball suspension system. The set point tracking and square wave tracking are done to test the performance of the controller. The efficacy of the proposed controller is evaluated based on the performance indices like overshoot, settling time, ISE and IAE. The stability of the system is analyzed using nyquist plot of the system. The results show that proposed hybrid ILC stabilizes the ball in the desired position.

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