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Optimization of Magnetic Levitation System

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Abstract:- In magnetically levitated system in certain applications like magnetically levitated train or bearingless motors the distance between the magnet and the levitated object has to be constant. The nonlinear system in such cases can be linearized and transfer function of the system is obtained. But a proper controller is required to manipulate the current through the magnet coil. The simplest controller to achieve this is the PID controller. But it was observed that as the levitated object deviated from the desired position, the gain of the PID controller set for one position did not hold good for some other position. Hence particle swarm optimization technique was implemented to determine the gains. Though optimal performance can be obtained for only one value of desired position y_{1d} of the object, but acceptable performance can be there for a small range of values of $y_{1d.}$ PID with PSO is found to be easy to implement, has stable convergence and good computational efficiency.

Keywords:- Magnetic Levitation, Controller, Optimization, Particle swarm optimization.

I. INTRODUCTION

In electromagnetic attraction type magnetic levitation system, the levitated object attains steady position when magnetic force and gravitational force are equal and opposite. Hence proper flow of current through the electromagnet coil is essential in suspending the object at the desired position. This is achieved by a controller. For applications like bearingless motors (Chiba 1995), maglev (Taniguchi 1992) etc where 'Y', the distance between the coil and the suspended object has to remain constant, the nonlinear system can be linearized and represented by a transfer function as presented by Trumper 1997,Shiao 2001 etc. By using a proper controller, the current through the coil can be made a function of 'Y' and the system can be stabilized. The controller used may be of proportional, integral and derivative (PID) type. Proportional, integral and derivative gains k_p, k_i and k_d are therefore dependent upon the desired value of 'Y' that is y_{1d}. In most of the cases only trial and error is used to determine these gains. It is observed that PID control law is easy to implement but has poor adaptability and the setting of parameters is difficult. In this work, particle swarm optimization (PSO) technique has been used to determine these gains. The method has an advantage that the objective function may have different weightage for overshoot, settling time and steady state error suiting to a particular application. Though optimal performance can be obtained for only one value of y_{1d}, but acceptable performance can be there for a small range of values of y_{1d}. PID with PSO is found to be easy to implement, has stable convergence and good computational efficiency with computation time 38 seconds in this particular case.

II. THE SYSTEM

A typical attraction type magnetic levitation set up developed by the author is as shown in Figure 1. 'E' shaped transformer laminations are used for making the core of the magnet. Windings on the side limbs (LC) are used for lifting the levitated object and winding on the central limb is used for detecting the separation 'Y' between the magnet and the levitated object. The side limb windings are connected in series in such a way that the fluxes Φ_1 and Φ_2 produced by them cancel each other in the central limb as shown in Figure 2. Therefore there is no mutual coupling between the coils on the side limbs and that on the central limb. The centre limb winding (SC) is used to obtain a voltage which is a function of variation in inductance of the coil with 'Y' and hence is a function of 'Y'.

The 'I' shape laminations were stacked together to form the suspended object. The details of the dimensions are specified in Figure 3 and Table I.

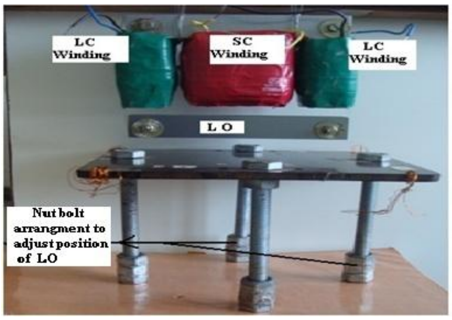


Figure1 Typical Attraction Type Magnetic Levitation System

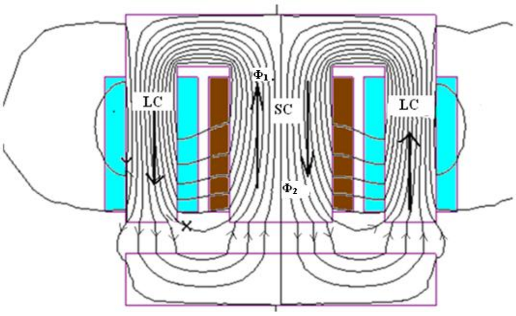


Figure 2 Flux pattern due to current in the lifting coil

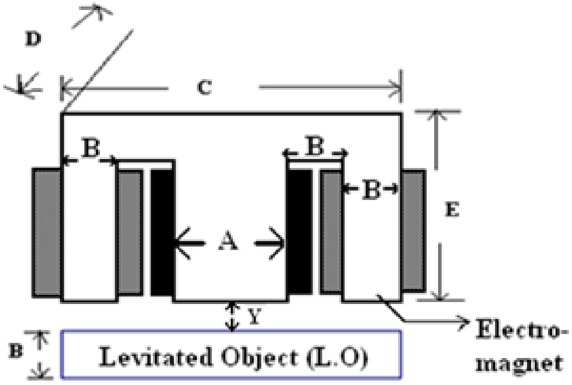


Figure 3 Dimensions of the electromagnet and levitated object

Table I Details of Dimensions

A=50mm	B=25mm	C=150mm
D=30mm	E=100mm	Y=10mm
Sensing Coil, R = 15 ohms L = 0.136 H		
Lifting Coil , R= 5 ohms L = 0.7H		
Mass of the levitated object =2.18 Kg.		

III. PID CONTROLLER

PID (proportional integral derivative) control is one of the earliest control strategies. In process control this controller is widely used. The controller can be tuned by using various formulae as discussed by Astrom, 1995. If only the proportional gain is introduced, the error reduces with increasing gain but the tendency towards oscillations increases. With PI control, the steady state error reduces or even disappears but oscillations increase with decreasing integral time. With the introduction of derivative control, damping improves but may also reduce for too large derivative time. So a proper value of PID gain need to be chosen.

Due to inductive winding of the electromagnet the current variation in the system is not responded instantaneously with the change in applied voltage. To improve the response of the system, the number of turns on the magnet can be reduced to decrease the winding inductance. But this may affect the stiffness of the system. To overcome this problem generally an inner current loop is added to the closed loop system and position loop forms the outer loop. The inner loop takes care of the instability and variation in parameters and hence accelerates the system as the position loop becomes independent to these parameters. To provide control for position control loop, it is known that only proportional gain is not sufficient to stabilize the system, a derivative gain also needs to be added such that the PD control takes care of the movement of the levitated object (LO). The PI controller is included in the inner current loop and controls the current to the coil. With a PID controller it is observed that time delay between coil voltage and its current is the main cause of oscillations of the levitated object. The problem can be mitigated by the use of a current source for energizing the coil.

Schematic of a typical controller for constant y_{1d} is shown in Figure 4. The desired position y_{1d} of the LO is compared with the actual position obtained through the position sensor. Depending on the error, the controller gives signal to the driver circuit. The VCCS accordingly supplies the required current to the LC winding so as to minimize the error. Schematic of a typical PID controller is shown in Figure 5. Opamp A and B are input and output buffers respectively. Opamp1 is an inverting amplifier whose gain can be set by resistances R_1 and R_2. This is set for the proportional gain. Opamp2 is a differentiating amplifier whose gain is set by capacitor C_1 and the resistance R_8. A small capacitor C_2 is connected in parallel with the resistor to prevent amplification of high frequency noise and ripples in the input.

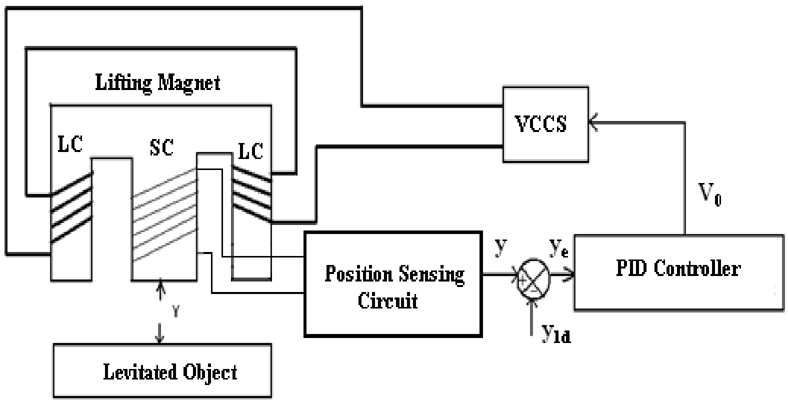
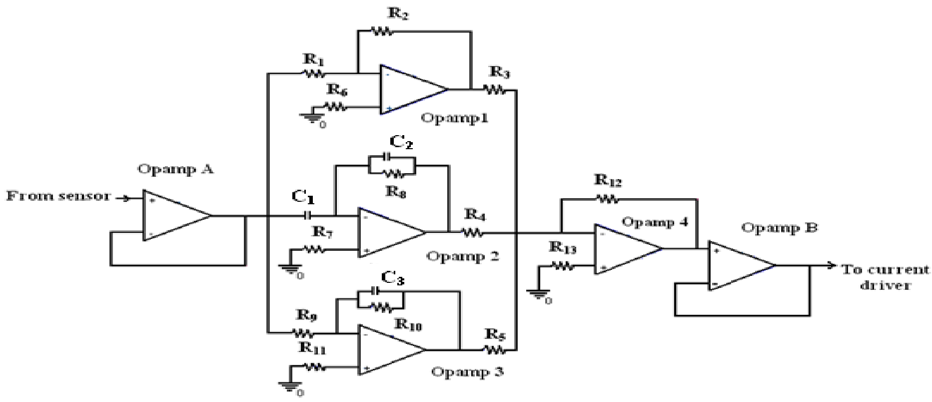


Figure 4 PID Controller Based Magnetic Levitation System for Constant 'Y'



R1=2.2k, R2=5k, R3=4.7k,R4=4.7k, R5=4.7k,R6=2.2k, R7=47k,R8=100k,R9=100k, R10=2.2k, R11=2.2k,R12=4.7k, R13=2.2kC1=0.22uf, C2=0.07uf, C3=0.22uf.

Figure 5 PID Controller Circuit

Opamp3 is an integrating amplifier whose gain can be adjusted by capacitor C_3 and resistance R_9. A high resistance in parallel with the capacitor is connected to prevent the run out of the integrator. Output from all the three channels are added up by a summing amplifier Opamp 4. Resistances R_3, R_4 and R_5 can be utilized to realize the weighted sum. Output of Opamp 4 is given to a current driver through Opamp B.

IV. SELECTION OF GAINS k_p, k_i AND k_d

IV.I Selection of the objective function

Gains kp, ki and kd are set by particle swarm optimization (PSO) technique. The objective function for the PSO depends upon the nature of the plant whose performance is to be optimized. A small step input is considered as a disturbance in y_{1d}. This is simulated in MATLAB and corresponding peak overshoot (M_p), settling time (t_s) and steady state errors (e_{ss}) are determined from the tool box for the system transfer function. The objective function equal to $A*M_p + B*t_s + C*e_{ss}$ is to be minimized. Depending on the application for which the PID parameters are optimized, the weightage of the parameters can be fixed. For example in case of bearingless motor, overshoot is highly undesirable as excessive overshoot might make the rotor to touch the stator and damage it. Steady state error should be reasonably low and time to settle may be large. Therefore for the system developed, the values of A = 80, B = 2 and C = 18 have been chosen by trial and error.

V. OVERVIEW OF PARTICLE SWARM OPTIMIZATION TECHNIQUE

PSO is a robust stochastic optimization technique based on the movement and cooperation of swarms. It applies the concept of social interaction to problem solving. It was first developed in 1995 by J. Kennedy and R. Eberhart. It uses a number of particles that constitute a swarm moving around in the search space looking for the best solution. Each particle is treated as a point in an N - dimensional (3 dimensional in this particular case) space which adjusts its "flying" according to its own flying experience as well as the flying experience of other particles (Hassanzadeh 2008). Each particle keeps track of its co-ordinates in the solution space which are associated with the best solution (fitness) that has achieved for by that particle. This value is called personal best, 'pbest'. Another best value obtained by any particle in any iteration made so far is called global best, 'gbest'. The basic concept of PSO lies in accelerating each particle towards its 'pbest' and the 'gbest' locations, with a random weighted acceleration at each time step. Each particle tries to modify its position using the information such as the current positions, the current velocities, the distance between the current position and 'pbest', the distance between the current position and the 'gbest'. The mathematical equations for the searching process are

$$V_i^{k+1} = WV_i^k + C_1 r_1 (pbest_i - S_i^k) + C_2 r_2 (gbest_i - S_i^k) \quad (4.1)$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \quad (4.2)$$

where

V_i^k = velocity of particle i at iteration k
w = weighting function
C_1 and C_2 = weighting factor
r_1 and r_2 = uniformly distributed random number between 0 and 2.
S_i^k = current position of the particle i at iteration k.
$Pbest_i$ = pbest of particle i
gbest = best value obtained by any particle among all the iterations performed so far.

The maximum velocity V_{max} determines the resolution of fitness regions which are searched between the present position and target position. If V_{max} is too high, the particle might fly past good solution. If V_{max} is too small, the convergence could be slower. According to experience of PSO, V_{max} takes often 10% to 25% of the dynamic range of the velocity.

V.I Weighting Function

The following weighting function is usually utilized in velocity update function

$$W = W_{max} - \frac{(W_{max} - W_{min}) * \text{present iteration number}}{\text{maximum iteration number}} \quad (4.3)$$

where

W_{max} = initial weight, W_{min} = final weight.

V.II PSO Parameters

The parameters chosen are as follows
Number of particles = 20
C_1 and C_2 = 5.8 and 6 respectively (values chosen based on the previous experience)
W_{max} = 1, W_{min} = 0.1
Number of iterations = 50

V.III PSO Algorithm

The searching algorithm of the proposed PSO-PID controller is given below.

1. Specify the lower and upper bounds of the three controller parameters and initialize randomly the individuals of the population including searching points, velocities, pbest and gbest.
2. For each initial individual of the population, calculate the values of the three performance criteria in the time domain, namely M_p, t_s and e_{ss} using MATLAB toolbox.
3. Calculate the objective function value (evaluation function value) of each particle for its kp, ki and kd.
4. Compare each individual's evaluation value with its Pbest. The best evaluation value among the pbest among all the iterations made so far is denoted as gbest.
5. Modify the member velocity of each individual
6. Modify the member position of each individual
7. If the number of iterations reaches the maximum, then go to Step 8. Otherwise, go to Step 2.
8. The individual that generates the latest gbest is an optimal controller parameter.

VI. SIMULATION RESULTS

The system is simulated with MATLAB using PSO based PID controller. The values of K_p, K_i and K_d obtained are 201.2, 5 and 175 respectively. The response of the system for a unit step input for the designed controller is shown in Figure 6. The peak overshoot is of 1.0162 at 0.4219 seconds and settling time is around 0.619 seconds.

The peak overshoot is acceptable, the settling time is not very high and the steady state error is zero. Compared to trial and error the PSO technique to optimize the PID parameters is more flexible. Weightage of the parameters can be adjusted as per the required performance and the type of application the system is designed for.

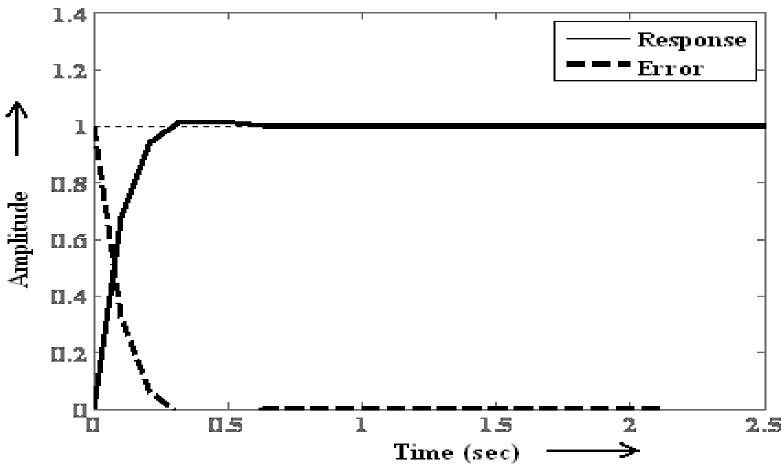


Figure 6 Step Response of the system

A PID controller is designed and optimized with PSO and the response obtained by simulation in MATLAB is as in Fig 6. But for the same PID controller if the position of the object is changed
from 0.02 to 0.01m, for the same kp, ki and kd values, the response obtained is as in Figure 7.
It shows that for deviation in position of the object, the valued of K_p, K_i and k_d needs to be modified to obtain proper response. Hence for applications where suspended object needs to be suspended at fixed position throughout, an optimized PID controller can be satisfactorily implemented. Whereas for applications like silicon wafer transportation as stated

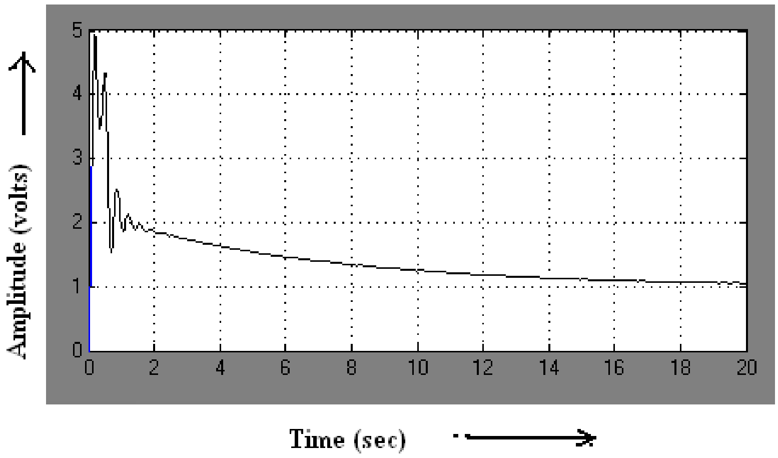


Figure 7 Step response of the system for change in Y from 0.02m to 0.01m

by Park(1998) where the object needs to be suspended at different positions from the magnet an adaptive or sliding mode controller can be designed.

VII. CONCLUSION

For magnetic levitation system if there is wide variation in the position of the suspended object from the magnet with respect to its desired position then PID controller alone is does not give satisfactory results. The gains set for this controller for a particular position of the object fails for change in position of the suspended object. Hence the gains for this controller are optimized so that the system works well for very small deviation of the object.

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