A Hybrid Control Approach For Large-Gap Magnetic Suspension System

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Abstract

This paper presents a hybrid control approach of a Self Tuning Fuzzy Controller plus a Proportional-Derivative (STF+PD) controller for wide range operation of a large-gap magnetic suspension system. Since the magnetic suspension system is highly nonlinear and inherently unstable in operation, the proposed STF controller is used to overcome the nonlinearity of wide range operation, and the PD controller is applied to stabilize the control system. Experimental results show that the STF+PD control approach is successful to wide range control of the magnetic suspension system.

I. INTRODUCTION

The large-gap magnetic suspension and balance system (LGMBS) is an inherently nonlinear and unstable system used in practices and studies. A proportional-derivative (PD) controller was first used by Sibier [11] to stabilize a ball for wind tunnel investigation of sphere. NASA Langley Research Center used a dual phase lead compensator to stabilize a five-degree of freedom 13-inch MSBS [3]. And a classical PID algorithm was used as controllers for MSBS which was commissioned at the National Aerospace Laboratory, Tokyo, Japan [3]. These practical results show that if the controlled operating range is relatively small, the control system may be reasonably approximated by a linearized system, whose dynamics is described by a set of linear differential equations. And the linear control theory can successfully be applied in the practical nonlinear unstable systems when the systems are only controlled near one operating point.

This paper concerns the dynamic tracking problem for position control in LGMBS. It is very important in wind tunnel test to get advanced aerodynamic data when the attitude of tested model is time varying. However, it is difficult to apply only linear state feedback controller for wide range controls in this highly nonlinear system, since the linear control theory often uses linearized model to design a controller. When the required operating range is large, a linear controller does likely perform very poorly or become unstable, because the nonlinearity cannot properly be compensated beyond certain range of operating point.

During the past few years, fuzzy control theory is one of the most active areas for practical control applications [4,12,13]. The fuzzy control theory is based on a set of fuzzy rules which are originated from human intuitions and "rules of the thumb" experience to design the controller. It does not concern carefully the dynamic system being linear or nonlinear, simple or complex. It seems to be easier and flexible to design a controller for a nonlinear system. However, to obtain high performance, much efforts should be devoted to modify the control rules regarding to system originality. It is lack of systematic analysis in design of the fuzzy controller. Sometimes the designers find it difficult to obtain adequate fuzzy rules, and often have to modify control rules by trials and errors to improve the performance.

Recently, self-organizing fuzzy controllers (SOFC) have been studied to develop and improve the fuzzy rule and structure automatically by monitoring the process performance index to obtain a predetermined quality [9,10]. The controller is composed of two levels, one is the basic level and the other is the self-organizing level. The basic level of the SOFC is actually a simple fuzzy controller. The self-organizing level
can modify the basic level according to the performance index. The performance index is organized by decision maker which issues the output correction from some fuzzy variables. The SOFC was successful applied in a heater temperature control and a motor speed control [10].

Until now, most of the performance index and rule modifier are only dependent on error and change in error to modify the basic level. It should be called as a regulator for a nonlinear system. Because the behaviors of a nonlinear system is not only dependent on error and change in error except only near one operating point, it does mainly depend on states of the system. For example, a wide range control of a magnetic suspension system has the described nonlinear behavior.

In this paper, a hybrid control concept is used to design controllers for wide range operation of one dimensional position control of a magnetic suspension system. The hybrid control concept combines a Self Tuning Fuzzy controller and a Proportional–Derivative (STF+PD) controller. The STF controller is used to overcome the nonlinear feature of wide range control, and the PD controller is used to stabilize the control system. The control purpose of the magnetic suspension system is to design a controller to track a time–varying reference input, such as sine wave. It should be remarked that "self tuning" is different from "self organizing". Because "self organizing" seems to be non–fixed–structure controller, and "self tuning" itself should be a fixed–structure controller. In this paper, a fixed–structure controller is used to simplify the design process. Buckley and Ying [1] described that the defuzzified output employing linear fuzzy control rules becomes a linear function of its input as the number of fuzzy control rules grows. Theoretically, a fuzzy logic controller can also be applied to stabilize the control systems. However, the linear control theory is well developed and becomes a systematic approach to determine the stability of a control system. Therefore, a PD controller is designed and implemented to stabilize the magnetic suspension in this paper.

The STF+PD controller is implemented into a PC–AT compatible computer to control the designed magnetic suspension system. The experimental results show that the proposed STF+PD controller is successful to reach the described control goal for the control of the magnetic suspension system.

II. SYSTEM DESCRIPTION & MATHEMATICAL RELATIONS

Fig. 1 shows the configuration of the magnetic suspension system. It consists of (1) a suspended object, (2) a sensor system, (3) a controller, (4) an amplifier, and (5) a magnetic coil.

The position of the suspended object is measured by the sensor system [8] using contact image sensor (CIS), and the signal is transformed into a computer (the controller). Combining the information of reference input and current state, the controller determines a control output signal using the STF+PD control approach. The output signal is amplified to control the coil current and then control the position of the suspended object. The overall system is shown in Fig. 2 with its actually fabricated system parameters shown in Table I.

![Fig. 1. Schematic diagram of the experimental magnetic suspension system.](image)

![Fig. 2. Photograph of the experimental control system.](image)

### Table I Parameters of magnetic suspension system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspended object diameter</td>
<td>50.0</td>
<td>mm</td>
</tr>
<tr>
<td>Suspended object mass m</td>
<td>16.5</td>
<td>g</td>
</tr>
<tr>
<td>Coil resistance R</td>
<td>52.0</td>
<td>Ohms</td>
</tr>
<tr>
<td>Coil inductance L</td>
<td>1.227</td>
<td>H</td>
</tr>
<tr>
<td>Servo gain G</td>
<td>0.2</td>
<td>A/V</td>
</tr>
<tr>
<td>Time constant τ</td>
<td>0.023</td>
<td>sec</td>
</tr>
<tr>
<td>Maximum control voltage</td>
<td>9.0</td>
<td>V</td>
</tr>
</tbody>
</table>
In the following, the mathematical model of the magnetic suspension system is presented. Neglecting the damping force due to the interaction of the air and the suspended object, the equation of motion for the suspended object and the voltage across the coil can be derived as:

\[ m \ddot{z} = m g - f(i, z) \]
\[ v_c = R i + L \frac{di}{dt}, \]

where \( m \) is the mass of suspended object, \( g \) is gravitational acceleration, \( v_c \) is a voltage across the coil, \( R \) is coil resistance, and \( L \) is coil inductance.

The linearized model is used for the PD controller. Let \( i(t) = i_0 + \delta i(t), z(t) = z_0 + \delta z(t) \); then \( f(i, z) \) can be expanded by Taylor’s series about an operating point where \( i = i_0, z = z_0 \):

\[ f(i, z) = f(i_0, z_0) + \frac{\partial f}{\partial i} \bigg|_{i_0, z_0} \delta i(t) + \frac{\partial f}{\partial z} \bigg|_{i_0, z_0} \delta z(t) + \text{higher order terms}. \]  

Under equilibrium conditions, the magnetic force is required to balance the gravitational force acting on the suspended object, that is:

\[ f(i_0, z_0) = m g. \]  

Let \( \frac{\partial}{\partial i} f \bigg|_{i_0, z_0} = k_{i0}, \frac{\partial}{\partial z} f \bigg|_{i_0, z_0} = -k_{z0} \); and \( v_c(t) = v_{c0} + \delta v_c(t) \), by neglecting the higher order terms, then Eqn. (1) and (2) can be derived as

\[ m \ddot{\delta z} = k_{z0} \delta z - k_{i0} \delta i, \]
\[ v_{c0} = R \delta i + L \frac{d\delta i}{dt}. \]

Therefore, Eqn. (5) and (6) can be combined into a Laplace transformed equation:

\[ X(s) = \frac{-k_{z0}}{(m^2s^2 - k_{i0})} \frac{1}{(R + sL)} V_c(s). \]  

The \( \frac{1}{(R + sL)} \) term is the transfer function from \( i(s) \) to \( V_c(s) \). The dynamics can be canceled by the technique of the virtual pole cancellation [6]. Indeed, the servo-amplifier is a high gain current feedback controller such that the dynamics of \( \frac{1}{(R + sL)} \) term can be theoretically canceled. In practice, the Eqn. (9) can be written as:

\[ X(s) = \frac{-k_{z0}}{(m^2s^2 - k_{i0})} \frac{1}{(1 + \tau s)} \frac{V_c(s)}{G} \]

where \( \tau \) is a time constant, \( G \) is the servo gain from the input voltage \( v(t) \) of the servo-amplifier to the output current \( i(s) \), and \( V(s) \) is the Laplace transform of \( v(t) \).

**Fig. 3.** Configuration of the proposed STF+PD controller.

### III. CONTROL SYSTEM DESIGN

Fig. 3 shows the configuration of the proposed STF+PD controller. The STF controller and PD controller is a parallel structure. The self-tuning fuzzy control is used to compensate the nonlinearity of magnetic suspension system for a wide range operation, such that the PD controller can stabilize the control system.

#### A. Self-Tuning Fuzzy Controller Design

Observing the linearization process as shown in Eqn. (3), the nominal term, \( f(i_0, z_0) \), should be the significant nonlinear term for the nominal operating term. If we can compensate this term, the linearized equation in Eqn. (5) and Eqn. (6) can reasonably be applied to design a stable controller. This is the main idea for conventional controllers. However, the controller designed under the linearized equation can only be operated near the operating point. If the operating range is large, especially tracking a time varying signal, the conventional controllers can no longer work well, because the system is inherently an unstable and nonlinear system. The nonlinear term, \( f(i_0, z_0) \), varies with different operating points.

From the above discussion, if we can change \( f(i_0, z_0) \) with respect to the position to be controlled in real time, then the linearized equation can still simulate the dynamics of the magnetic suspension system very well. However, it is difficult to measure \( f(i_0, z_0) \) term exactly, because the magnetic suspension system is originally an unstable system. In general, the nonlinear term is not only dependent on position \( z_0 \) but also a time varying term due to environmental temperature.

This is the main idea to construct a self-tuning fuzzy controller to compensate the nonlinear term \( f(i_0, z_0) \). The procedures are following:

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1. Define fuzzy labels corresponding to some operating points and their associated membership functions.
2. Construct database, corresponding to these fuzzy labels, which record the information of the nonlinear term \( f_{(0,0)} \).
3. Determine the compensate term \( f_{(0,0)} \) from database.
4. Tune the database in real time by the reference input and state information — self-tuning process.

Procedure (1) and (2) are pre-defined. They are the knowledge bases of the FLC. Procedure (3) and (4) are really on line self-tuning fuzzy controller.

Eleven fuzzy labels are defined in this paper: \( P_i \) for \( i = 1, 11 \). The support values corresponding to these fuzzy labels are \( x = 0 \) mm to 100 mm with equal interval of 10 mm each. The associated membership functions are triangular types as shown in Fig. 4. The data base, named \( V \) for \( i = 1, 11 \), records the voltage of the equilibrium points corresponding to the support value of the fuzzy label.

\[
C_{V}(r, z) = \Delta V_{P_i} = \beta \mu_{P_i}(r)(r-z), \tag{11}
\]

where \( \beta \) is a tuning factor which is similar to the integral gain for a PID controller, and \( \mu_{P_i}(r) \) is a membership function.

Then, the nonlinear effect of the wide-range operation can be compensated by the self-tuning fuzzy controller.

B. PD Control Design

While the nonlinear effect is compensated by the self-tuning fuzzy controller, the linear dynamic equation can simulate the magnetic suspension system. The remaining work is to design a linear controller to stabilize the system. Observing the transfer function in Eqn. (6), the parameters, \( k_{br} \) and \( k_{so} \), are still varying with respect to different operation points. It makes no significant concern if the worse case is considered to design a stabilized controller. If the control cannot be achieved, a gain scheduling controller can be applied to overcome the design difficulty.

IV. EXPERIMENTAL RESULTS

The PID controller and the STF+PD controller are implemented into a PC-AT compatible computer. The 80287 math coprocessor is used to speed up the calculation of floating-point numbers. The program for transforming the input/output data is written in Fortran language, and the PID controller and the STF+PD controller are written in Assembly language. The sampling frequency is set at 200 Hz by a programmable counter and timer chip 8254.

Assume that the control parameters for the PID controller are \( K_p = -125 \), \( K_i = -125 \), and \( K_d = -12.5 \), and the STF+PD controller are \( \beta = -125 \times 0.005 \), \( K_p = -125 \), and \( K_d = -12.5 \), where the factor, 0.005, is sampling time such that the value of \( \beta \) is similar to one of \( K_i \). Fig. 5 shows the step responses of the proposed STF+PD controller when \( r(t) = 60 \) mm is applied. The name "Initial run" is assigned to the control results of STF+PD controller when the fuzzy data, \( V_{P_i} \), are initialized by zeros. This means that the force model \( f(i, z) \) is not initially known. The name "Further runs" is assigned to other control results after the initial run. If the initial run converges then the fuzzy data will converge, so the control results of further runs will keep the same when the plant parameters are fixed. The nominal term \( f_{(0,0)} \) is exactly tuned by the STF controller after the initial run. The step response of the PID controller is similar to the initial run of the STF+PD controller which there is significant delay compared with the further runs of the STF+PD controller. Fig. 6 shows the
tracking effects of the STF controller for reference input \( r(t) = [60 + 15 \sin(0.2 \pi t)] \) being applied. However, the PID controller fails for the tracking case.

V. CONCLUSION

In this paper, a hybrid STF+PD controller is proposed to wide range operation of one dimensional position control of the magnetic suspension system. The STF controller derived based on compensating the nominal term — operating control signal is used to overcome the nonlinearity of the magnetic suspension system. The advantage of the STF controller is that even if the the nominal term is not exactly known, the tuning process will modify the nominal term to true value and will result good further operation. The concept is very simple, and the control system is not complicated. From the experimental results, the proposed hybrid control approach is successfully used for the wide range control of the magnetic suspension control system. The control concept will be extended to wide range control of a MIMO system such as wind tunnel magnetic suspension system.

REFERENCES

利用混合式控制在磁浮懸吊系統的探討

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本文論文利用混合式的控制方法使磁浮懸吊系統作大範圍操控控制。而本文所談及的「混合式控制」包括自調調整式的模糊控制器與PD控制器。自調調整式的模糊控制器主要是用來即時提供不同操作點所需的平衡側流，使整個系統可用PD控制器加以穩定。由實驗的結果可見本文所提出的混合式控制的方法不僅操作上相當簡單，且可以很成功的運用在實際的非線性不穩定系統上，使其作大範圍的操控控制。