Digital Controller Design to Mitigate Chaotic Vibrations In Magnetic Levitation System

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Abstract—This article presents digital control algorithm to quench the chaotic behavior in nonlinear magnetic levitation system. The system dynamic modeling is reviewed. Results of the open loop system behavior are summarized. A digital control algorithm is proposed and closed loop system is simulated and analyzed using its state trajectories. The proposed control algorithm is simpler in structure, has optimized convergence time, eliminates the chaotic behavior of system and allows the system to synchronize with an external reference signal. The experimental validation of the theoretically proposed controller is also presented by implementing the discrete time realization of the control algorithm using digital controller interfaced in the real-time, using MATLAB/Simulink, in the Rapid Control Prototyping (RCP) mode of operation. The feasibility of the proposed design is theoretically and experimentally verified by its efficiency performance and ease of digital implementation.

Keywords—Chaos; Magnetic Levitation System; Chaotic Synchronization; Feedback linearization; Rapid Control Prototyping

I. INTRODUCTION

The study of chaos in the perspective of control theory has been in boom over the last few decades [1]. The theory of chaos is one of the most stirring and quickly growing research topics [2]. The response of system with chaos can be tolerable in some of the scenarios, however most of the mechatronic systems suffer deterioration owing to chaotic behaviors hence limiting the operable region of the system to retain the performance index within permissible bounds. Therefore, it can be inferred that when dealing with chaotic systems the objective is to mitigate chaotic behavior in majority of the cases [3] In many problems the objective involves synchronization of two chaotic systems which is achieved by synthesizing a controller that forces the chaotic system to follow a given reference signal [4,5]. Many strategies are developed and tested to subdue the chaotic responses of the systems. Now-a day the application of chaotic theory for magnetic suspension system has gained a pace and many strategies have been proposed [6].

Magnetic Levitation (Maglev) is a very stimulating system. It consists of suspending a ferromagnetic body in the space against the force of gravity. It is characteristically nonlinear and unstable. The feedback is inevitable to stabilize this system [7,8]. This setup acts as a standard for research of trains that work on the principle of Magnetic levitation. The vehicles based in magnetic levitation run more smoothly and somewhat more quietly than wheeled mass transit systems. The Maglev vehicles do not depend on traction and track friction, which means that acceleration and deceleration can outstrip that of wheeled transports, and they are unaffected by weather. The power required for levitation is normally not a big percentage of the total energy intake [9]. The conveyor belts based on Maglev principle are used for materials transport systems.

The availability of cheap and efficient digital controllers has made the digital control domain very desirable for system automation [10,11]. This paper considers digital algorithm design for mitigating the chaotic behavior of system followed by the synchronization of system response with an external reference. The theoretical formulation is simulated. System operation in Rapid Control Prototyping mode is achieved. The theoretical results are experimentally verified and feasibility of proposed control algorithm is validated.

II. EXPERIMENTAL SETUP AND SYSTEM DYNAMICS

Fig. 1 shows the schematic diagram of the hardware setup. It consists of two annular permanent magnets (PM) and they are free to slide over a vertical nonmagnetic guide pipe. The similar poles of annular magnets face each other, which causes upper magnet to be levitated above the lower magnet. The vertical displacements of both magnets are monitored by non-contact proximity technique using ultrasonic sensors. The displacement of lower magnet is controlled by an electromechanical actuator. The displacement of upper magnet can be controlled by an electromagnetic.
Fig. 2 shows the actual experimental setup used in this work, for the experimental verification of control algorithm. This setup incorporates digital controller and data acquisition card. These interfaces provide a means for implementation of hardware in loop Rapid Control Prototyping scheme, for real time data monitoring and control. Actuator coil drive board is also visible in this setup.

The system dynamics are given by,

\[
\frac{d^2 p_i}{dt^2} = \frac{1}{m_i} F_c + \frac{g(p_{10} - p_{i0})^2}{(p_i - p_{i0})^2} + g \cdot \frac{B}{m_i} dp_i
\]  

(1)

Here \( p_{10} \) and \( p_i \) are positions of permanent magnet PM1 and PM2 respectively, above the pedestal. The free body diagram of the system is shown in Fig. 3, \( F_c \) is the upward force generated by electromagnetic coil on PM2, \( F_g \) is the downward force of gravity on PM2. \( F_{10} \) is the force of repulsion exerted on PM2 by PM1, \( m_i \) is the mass of PM2, \( B \) is the frictional constant, \( p_{i0} \) is the nominal value of \( p_i \).

Defining the system states as,

\[
x_i = p_i
\]

\[
x_j = \dot{x}_j
\]

We get the following state space model,

\[
\begin{align*}
\dot{x}_i &= x_j \\
\dot{x}_j &= \frac{g(x_{i0} - p_{i0})^2}{(x_j - p_{i0})^2} \cdot g + \frac{B}{m_i} x_j + u
\end{align*}
\]

Let us define an error variable in (5) and control law in (6).
Using (4) and (5), we get the error dynamics,

\[ c \dot{c} = 0 \] (6)

If control is turned on at time \( t = T \), then the convergence time under the boundary condition \( \phi(0) = x_1(T) - r(T) \) for (6) is given by

\[ t_{\text{con}} = \frac{1}{c} \ln \left( \frac{\phi(0)}{c \phi(0)} \right) \]

where \( \phi \) and \( c \) are constants. We can find the optimal value of \( c \) by minimizing the convergence time. This value is given by,

\[ c_{\text{opt}} = \frac{\phi(0)}{\phi(0)} \] (7)

The above results lead \( e(t) \to A \) as \( t \to t_{\text{con}} \), where \( A \) is a constant and \( x_1(t) \to r(t) + A \). By appropriately offsetting the reference command, the steady state error \( A \) in \( x_1 \) can be mitigated. Using above results the value of current in electromagnetic coil is given by,

\[ i = \frac{m(p_1 - p_2)^2}{k} \left( -f - cx_2 + \phi c \phi \right) \] (8)

### III. Simulation and Testing

The values of various system parameters are given in Table 1. Using these values the digital system in simulate in Fig. 3. The boxes with the grey background correspond to the digital implementation of proposed control strategy.

<table>
<thead>
<tr>
<th>TABLE I. VALUES OF SYSTEM PARAMETERS</th>
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<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>( m )</td>
</tr>
<tr>
<td>( B )</td>
</tr>
<tr>
<td>( g )</td>
</tr>
<tr>
<td>( x_{\text{ib}} )</td>
</tr>
<tr>
<td>( p_\text{m} )</td>
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The displacement of PM2 is plotted in Fig. 4. It is clear that response proceeds chaotically with time. Fig. 5 shows the velocity response of PM2, which is equally chaotic.

Fig. 6 shows the chaotic system trajectories long time span respectively. The system maps are chaotic and it is clearly visible in this figure.

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Figure 3. Digital control algorithm simulation

Figure 4. Open loop response of PM2 displacement.

Figure 5. Open loop response of PM2 velocity.
Fig. 6 shows the open loop system state trajectories over a long-time span. It is clearly visible that the controller is not only able to quench the chaotic behavior but has also enabled the system to follow the commanded reference sinusoidal signal. This is effectively equivalent to synchronization of the system with an external commanded reference.

Fig. 7 shows the closed loop response of PM2 displacement. The controller is turned on at t=9sec. Without the controller turned on, the system state trajectories are chaotic, however, as the controller turns on the system state trajectories converge to a predefined reference trajectory. This trajectory is showed zoomed-in in Fig. 8. Fig. 9 shows the plant input signal. As the controller is turned on at t=9sec, the actuating signal becomes active and stays bounded.

IV. EXPERIMENTAL RESULTS

The block diagram of RCP mode of operation of hardware is shown in Fig. 10.
The Simulink setup for RCP mode is shown in Fig. 12. Fig. 11 shows the experimental closed loop response of PM2 displacement. The controller is turned on at t=9sec. It is clearly visible that controller is not only able to quench the chaotic behavior but has also enabled the system to follow the commanded reference sinusoidal signal. This is effectively equivalent to synchronization of the system with an external commanded reference. Fig. 13 shows the experimental closed loop system state trajectories with controller turned on at t=9sec. Without the controller turned on, the system state trajectories are chaotic, however, as the controller turns on the system state trajectories converge to a predefined reference trajectory. This trajectory is showed zoomed-in in Fig. 13.
A control algorithm is presented to suppress the chaotic behavior of a nonlinear magnetic levitation system. The open loop system dynamics are presented followed by control algorithm design. The open loop system response is simulated and analyzed for the chaotic behavior. The closed loop system is simulated and its response is analyzed. The responses clearly manifest the success of designed control algorithm to quench the chaotic behavior in system state trajectories and allow the system trajectories to converge to a predefined reference trajectory.

REFERENCES