Implementation and Model Verification of a Magnetic Levitation System

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Abstract—This paper presents the implementation of a two degree-of-freedom magnetic levitation system employing one permanent magnet linear synchronous motor, and the experimental validation of a mathematical model previously derived. The paper focuses on showing the development of a calibration procedure to estimate model parameters and its subsequent use for model verification. Experimental results show that the proposed mathematical model accurately describes the dynamics of the system over a wide operating range showing promise for the future implementation of nonlinear controllers.

I. INTRODUCTION

In semiconductor manufacturing, many process stages require positioning systems, referred to as microsteppers, capable of several degrees of freedom (DOF) with significant speed and precision [1]. As the pace of technology causes the dimensions of semiconductors to further decrease, there is an increasing interest, in industry, to replace traditional mechanical microsteppers by contactless positioning devices. This arises from the fact that mechanical contacts introduce impurities that may limit the accuracy of the photo-lithographic process, thus decreasing production throughput. Further, mechanical positioning devices require costly maintenance due to the wear of their components.

In [2], Kim and Trumper proposed a contactless microstepper which employs single sided air cored permanent magnet linear synchronous motors (PMLSM) to actuate six degrees-of-freedom. Individually, PMLSMs produce both a normal and translational force with appropriate control. When several are combined in appropriate fashion, multiple degrees of freedom can be achieved. In [3], modelling and nonlinear control designs are presented for an idealized three degrees-of-freedom device which employs iron cored PMLSMs. This device was designed to work over a large range of operation and to employ standard PMLSMs commonly found on the market.

This paper initiates the experimental verification of the theory developed in [3] using a simplified 2-DOF apparatus constructed by Quanser Consulting. We use a parameter identification technique developed in [4] to estimate the parameters of the model in [3] and then compare the behavior predicted by the model to what is actually observed. Such comparison demonstrates accuracy of the model over a wide range of operation (100 mm × 10 mm). Future work will focus on the implementation of nonlinear controllers based on the designs in [3].

We begin our discussion with a description of the magnetic levitation hardware utilized during experimentation, along with a brief summary of the model derivation. This is followed by the parameter identification technique found in [4]. The actual model verification procedure is then presented in conjunction with a series of experimental results. The paper concludes with a description of future extensions to the magnetic levitation implementation.

II. DESCRIPTION OF 2-DOF HARDWARE

A photo of the 2-DOF hardware implementation is shown in Figure 1. As mentioned earlier, we employ a single sided iron-cored PMLSM.

Fig. 1. 2-DOF magnetic levitation hardware implementation

The stator of the PMLSM, which is fixed in place to a heavy aluminium frame, is longitudinally laminated and transversally slotted in order to accommodate a single layer of 3-phase winding. The mover, which is attached to two orthogonally mounted linear guides allowing for horizontal and vertical movement, is composed of a set of four type N35 permanent magnets (PM) attached to a ferromagnetic backing. The details of the hardware specifications are summarized in Table I.

The 3-phase AC current required to actuate the stator coils is provided by a set of three linear current amplifier modules (LCAM) which are sent commands via a PC. The horizontal and vertical position information is provided to the PC by two linear optical encoders with a resolution of 10 µm. Controllers are implemented using the WINCON real-time code generator with Simulink as an interface.
With the current setup, the 2-DOF magnetic levitation system has a horizontal range of approximately ±50 mm and a vertical range of approximately ±10 mm. The goal is to eventually design a nonlinear controller to obtain positioning and tracking accuracy of at least 0.1 mm over the above-mentioned horizontal range and a vertical range of ±5 mm with as much speed as possible.

III. MODEL OF 2-DOF SYSTEM

The following is a brief summary of the model derivation applied to the 2-DOF system. The details of the modelling are found in [3].

Consider the inertial frame of the single PMLSM that forms the basis of the 2-DOF system, which is shown in Figure 2. Let $L_A$ be the depth of each PM along the z-axis, $h_m$ be the height of the magnets, $p_m$ the number of PM’s, $g$ the air-gap length, $t_1$ the slot pitch, $b_0$ the slot aperture, $\tau$ the PM pole pitch, $\tau_p$ the PM pole arc, $\mu_{rec}$ the relative PM recoil permeability, and $\sigma_m$ the surface magnetic charge. To account for the effects of the stator slots, replace the air-gap $g$ by the effective air-gap $g_c$, with $g_c = g \frac{K_c}{\mu}$, where $K_c$ denotes Carter’s coefficient. In addition, let $I_a$, $I_b$, and $I_c$ be the phasors of the phase currents and $I_a$, $I_b$, and $I_c$ their magnitudes. Define $W$ to be the number of turns of wire on each phase, $p$ the number of pole pairs in the stator, $w_c$ the coil pitch, and $\kappa_{w1}$ the winding factor.

We define the horizontal motion to be along the $x$-axis while vertical motion is fixed to the $y$-axis. Defining $G$ as the gravitational acceleration and $M_h$ and $M_v$ as the horizontal and vertical masses of the platform to be levitated, the following 2-DOF system model is obtained:

$$
\begin{align*}
\dot{x}_1 &= x_2, \\
\dot{x}_2 &= G - L_4(x_1)[u_1^2 + u_2^2] - L_3(x_1)u_2 - L_2(x_1), \\
\dot{x}_3 &= x_4, \\
\dot{x}_4 &= -L_1(x_1)u_1,
\end{align*}
$$

(1)

The above model does not account for friction, cogging forces, and end effects. It is necessary to verify to what extent such unmodled effects can be neglected within a reasonable range of operation. This is done in the following.

IV. SYSTEM ID METHODOLOGY

We begin by lumping all constant unknown (or not perfectly known) parameters and rewriting (1) as

$$
\begin{align*}
\dot{x}_1 &= x_2, \\
\dot{x}_2 &= G - C_4 \frac{\tilde{\lambda}(x_1) \coth^2(\frac{\pi}{\tau}(h_m + x_1))}{K_c^2(x_1)}[u_1^2 + u_2^2] \\
&\quad + C_3 \frac{\tilde{\lambda}(x_1)B_{pmy1}(x_1) \coth^4(\frac{\pi}{\tau}(h_m + x_1))}{K_c(x_1)}u_2 \\
&\quad - C_2 \frac{\tilde{\lambda}(x_1)B_{pmy1}(x_1)^2}{K_c(x_1)}u_1, \\
\dot{x}_3 &= x_4, \\
\dot{x}_4 &= -C_1 \frac{\tilde{\lambda}(x_1)}{\kappa_{w1}(x_1) \sinh(\frac{\pi}{\tau}(h_m + x_1))}u_1,
\end{align*}
$$

(2)
where \( C_1, \ldots, C_4 \) are lumped constants to be determined experimentally and have the following form

\[
C_1 = \frac{12 \sqrt{2} \pi k_{\omega} \mu_p L_a \sigma \pi \mu_0 \sinh(\frac{\pi h_0}{h_{\sigma}}) \sin(\frac{\pi h}{h_{\sigma}})}{M_n \tau_p},
\]

\[
C_2 = \frac{L_a \mu_0}{M_4 \mu_0},
\]

\[
C_3 = \frac{3 \sqrt{2} L_a \mu_0 W \kappa_{\omega}}{M_4 \mu_0},
\]

\[
C_4 = \frac{18 L_a \mu_0 W^2 \kappa_{\omega}^2 \mu_0}{M_4 \tau_p^2}.
\]

Noticing that \( C_1, \ldots, C_4 \) enter the model linearly, we employ the technique presented in [4] to estimate them. For the sake of illustration, in what follows we briefly review the parameter identification technique in [4].

Consider the nonlinear system

\[
\dot{x} = A(x, u)\theta + b(x, u) + \omega(t), \quad x(0) = x_0,
\]

where \( \theta \) is a vector of constant unknown parameters, all functions are smooth, and \( \omega(t) \) is an \( L_\infty \) disturbance. It is assumed that a noisy measurement of the state \( x \) is available,

\[
y = x + \varepsilon \nu(t),
\]

where \( \nu(t) \) is the measurement disturbance and \( \varepsilon \) is a known scalar. The value of \( \varepsilon \) reflects the confidence level in the state measurement. The simplified approximation to the \( H_\infty \) optimal NPFSI (noise-perturbed full-state information) estimator, referred to as the reduced-order NPFSI estimator, was given in [4] as follows:

\[
\hat{\theta} = \varepsilon^{-1} \Sigma^{-1} A(y, u)^T(y - \hat{x}), \quad \hat{\theta}_0(0) = \hat{\theta}_0,
\]

where

\[
\dot{\hat{x}} = A(y, u)\hat{\theta}_x + b(y, u) + \varepsilon^{-1}(y - \hat{x}), \quad \hat{x}(0) = \hat{x}_0,
\]

\[
\dot{\Sigma} = A(y, u)^T A(y, u) - \gamma^{-2} Q(y, u), \quad \Sigma_0(0) = Q_0.
\]

In the above, \( \gamma \) represents an attenuation factor that can be tuned to improve estimator convergence. It is proven in [4] that if the system under consideration satisfies a suitable persistency of excitation condition and \( \varepsilon \) is sufficiently small, the state of (3) converges to the true parameters.

Although the NPFSI technique does not require state derivative information, it does depend on measurement of the full state vector. While the position states \( x_1 \) and \( x_3 \) are measured directly using optical encoders, the velocity states \( x_2 \) and \( x_4 \) are not measured. To overcome this problem, we use high-gain observers to estimate \( x_2 \) and \( x_4 \). The estimation errors are accounted for, in the parameter identification procedure, by the assumption that a noisy measurement of the states is available. Further, to guarantee persistency of excitation, we employ two PID regulators for the control inputs \( i_d \) and \( i_q \) to independently make the horizontal and vertical dynamics track a suitable reference signal made of a summation of sinusoids at various frequencies.\(^2\)

\(^2\)Clearly, because the horizontal and vertical dynamics of the system are not decoupled (see (1)), PID control does not yield good tracking performance. However, since at this stage we only focus on the generation of persistently exciting reference signals for parameter estimation, tracking accuracy is not a concern.

With the above in place, the only remaining issue is the choice of the NPFSI parameters \( \gamma \) and \( \varepsilon \). It was found through successive experimentation that choosing \( \gamma \approx 1.1 \) and \( \varepsilon \approx 0.01 \) produced good parameter convergence.

The estimator structure in (3) is used, in what follows, in three different ways. First, to verify the horizontal dynamics. Second, to estimate \( C_2, C_3, \) and \( C_4 \) and verify the vertical dynamics. Lastly, to estimate \( C_1, \ldots, C_4 \) and simultaneously verify horizontal and vertical dynamics. This is explained in detail in the next section.

V. MODEL VERIFICATION PROCEDURE

With a model of the 2-DOF magnetic levitation system in place along with a technique to estimate the physical parameters, the next task is to develop a procedure capable of verifying the accuracy of said model in predicting the behavior of the actual magnetic levitation system.

A. Verification of Horizontal Dynamics

If the air-gap of the magnetic levitation system is fixed to a constant value \( \bar{x}_1 \), then the horizontal dynamics from (1) (or (2) equivalently) can be isolated

\[
\dot{x}_3 = x_4, \quad \dot{x}_4 = -L_1(\bar{x}_1)u_1.
\]

Since at a fixed air-gap \( \bar{x}_1 \) the \( L_1 \) term is constant, the horizontal position \( x_3 \) can be solved easily

\[
x_3(t) = -\frac{1}{2} L_1(\bar{x}_1)u_1 t^2 + x_3(0).
\]

Note that an initial horizontal velocity of zero is assumed. Equation (5) tells us that if a constant \( u_1 \) is applied to the system when the air-gap is fixed, the horizontal position of the mover exhibits a parabolic response. By recording the horizontal position information subject to these conditions, it should therefore be possible to curve-fit a parabola to the data points and obtain an estimate of \( L_1(\bar{x}_1) \) at the air-gap in question (and therefore an estimate of the horizontal acceleration of the mover). Such estimate is compared to the value of \( L_1(\bar{x}_1) \) obtained applying the NPFSI estimator to (4). This idea is summarized below.

- The motion of the system is constrained (by hardware) to lie on the horizontal axis.
- Position data are collected corresponding to different air-gap values \( \{\bar{x}_1^1, \ldots, \bar{x}_1^k\} \).
- A set of parabolas is fitted to horizontal position data at various air-gaps \( \{\bar{x}_1^1, \ldots, \bar{x}_1^k\} \) in order to obtain an estimate of \( L_1(\bar{x}_1^i), i = 1, \ldots, k \) by means of (5).
- For each air-gap \( \bar{x}_1^i \), the NPFSI estimator (3) is applied to (4) to estimate \( L_1(\bar{x}_1^i) \) and the results are compared.

Figure 3 shows a few examples of the data points obtained and the parabolas that were fitted. Note how the parabolic curves closely approximate the position data, demonstrating the correctness of the horizontal dynamics model (4). Air-gap values here range between 10 and 27.5 mm at 2.5 mm intervals. In each case, the mover is started
then be isolated
\[ \ddot{x}_1 = x_2, \]
\[ \ddot{x}_2 = G - L_4(\ddot{x}_1)u_2^2 - L_3(\dddot{x}_1)u_2 - L_2(\dddot{x}_1). \]  

From (6), we have that the current \( \bar{u}_2 \) needed to maintain the air-gap at a desired equilibrium \( \dddot{x}_1 \) is found by solving
\[ G - L_4(\dddot{x}_1)u_2^2 - L_3(\dddot{x}_1)u_2 - L_2(\dddot{x}_1) = 0. \]  

If the model (6) associated with the vertical dynamics is correct, the equilibrium current \( \bar{u}_2 \) predicted by (7),
\[ \bar{u}_2 = -L_3(\dddot{x}_1) - \sqrt{L_3^2(\dddot{x}_1) - 4L_4(\dddot{x}_1)(L_2(\dddot{x}_1) - G)} \]
\[ 2L_4(\dddot{x}_1), \]  
should be close to the measured equilibrium current. The validation procedure for the vertical dynamics is now clear.

- The motion of the mover is constrained (by hardware) to lie on the vertical axis at \( x_3 = 0 \) mm.
- Set \( u_1 = 0 \).
- For air-gaps in the set \{\( x_1^1 \), ..., \( x_1^N \)\}, the corresponding equilibrium currents \{\( u_2^1 \), ..., \( u_2^N \)\} are measured.
- The NPFSI estimator is applied to (6) to estimate the constants \( C_2, C_3, \) and \( C_4 \) and obtain \( L_2, L_3, \) and \( L_4 \).
- The terms \( L_2, L_3, \) and \( L_4 \) are used to determine the theoretical equilibrium currents by means of (8).
- The theoretical equilibrium currents are compared to the measured currents.

We choose the air-gap values to range between 10 and 25 mm with 1 mm increments. The NPFSI estimator is applied for three different values of \( \varepsilon \). The estimation results are summarized in table II.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>( \varepsilon = 0.001 )</th>
<th>( \varepsilon = 0.01 )</th>
<th>( \varepsilon = 0.05 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_2 )</td>
<td>990.97</td>
<td>991.00</td>
<td>788.98</td>
</tr>
<tr>
<td>( C_3 )</td>
<td>30.47</td>
<td>30.90</td>
<td>32.44</td>
</tr>
<tr>
<td>( C_4 )</td>
<td>0.11</td>
<td>0.12</td>
<td>0.18</td>
</tr>
</tbody>
</table>

In Figure 5 the theoretical equilibrium currents found using the parameters \( C_2, \ldots, C_4 \) estimated with \( \varepsilon = 0.01 \) are compared to the measured equilibrium currents.

From the plot, It is clear that while the model begins to diverge from the physical measurements for air-gaps smaller then 15 mm, within the range between 15 and 25 mm the model accurately describes the behavior of the magnetic levitation system. The results therefore validate the vertical dynamics of the model within the range of 15 and 25 mm and further validates the NPFSI technique.

The divergence below 15 mm is most likely the result of uncertainties that are not taken into account within the model. In what follows, evidence is provided that suggests the cogging force accounts for most of the uncertainty.

**B. Verification of Vertical Dynamics**

To validate the vertical dynamics, we fix the mover at \( x_3 = 0 \) mm to only allow vertical motion. We also set \( u_1 = 0 \). The vertical portion of (1) (or (2) equivalently) can
The normal force should accurately be represented by $F$. The PMLSM on the surface of the mover is given by

$$F = \xi(x_1) \sin \left( \frac{\pi}{t_1} x_3 \right). \tag{9}$$

The function $\xi(x_1)$, representing the peak magnitude of the cogging force, is typically inversely proportional to the air-gap $x_1$, meaning that the cogging force gets stronger as the mover gets closer to the stator. Notice that the peaks of the cogging force occur at odd integer multiples of $t_1/2 = 9.525$ mm. Hence, if the mover is held at the position $x_3 = 28.575$ mm, then the total normal force exerted by the PMLSM on the surface of the mover is given by

$$\left. F_n(x_1) \right|_{x_3=3t_1/2} = K_2(x_1) + K_3(x_1) u_2 + K_4(x_1) u_2^2 + \xi(x_1)$$

where, as before, we are setting $u_1 = 0$. On the other hand, when $x_3 = 0$ mm, the cogging force vanishes and thus the normal force should accurately be represented by

$$\left. F_n(x_1) \right|_{x_3=0} = K_2(x_1) + K_3(x_1) u_2 + K_4(x_1) u_2^2.$$

Since the unknown constants $C_2$, $C_3$, and $C_4$ in the functions $K_2$, $K_3$, and $K_4$ have already been estimated in the previous section, to estimate $\xi(x_1)$ we let $\tilde{K}_2(x_1) = K_2(x_1) + \xi(x_1)$, estimate $\tilde{K}_2$ and get $\xi(x_1) = \tilde{K}_2(x_1) - K_2(x_1)$. This simple idea is the basis of the next procedure.

- The constants $C_3$ and $C_4$ are assumed to be known and equal to the values estimated in the previous section. The constant $C_2$ is assumed to be unknown and is estimated by applying the NPFSI estimator to $\xi(x_1)$.
- The value of $C_2$ just found is used to generate an approximation of $\tilde{K}_2(x_1)$ as

$$\tilde{K}_2(x_1) = C_2 \hat{\lambda}(x_1) B_{pmy1}(x_1)^2.$$

- The difference $\tilde{K}_2(x_1) - K_2(x_1)$ represents an estimate of the peak cogging force as a function of the air-gap.

Applying the above procedure and using $\varepsilon = 0.01$ in the NPFSI estimator we get $C_2 = 769.99$. This gives the estimate of $\xi(x_1)$ depicted in Figure 6. This clearly illustrates that the estimated peak cogging force is appreciable (greater than 1 N) when the air-gap is smaller than 15 mm, and otherwise negligible for larger air-gaps.

This is confirmed in Figure 7, where the theoretical equilibrium currents are compared with the actual measurements of $u_2$ with and without the horizontal offset. While the two predictions are almost identical over most of the air-gap range, they diverge at air-gaps smaller than 15 mm.

Since the value of the normal force over the range of operation is of the order of 10 N, it is clear from Figure 6 that, within the air-gap range between 15 mm and 25 mm, the cogging force at each horizontal position is a relatively small percentage of the total force, and can be ignored in this range. However, Figure 6 indicates that for smaller air-gaps the discrepancy may become significant.

**D. Verification of Complete Model Dynamics**

With the horizontal and vertical dynamics of the system verified, the final task is to confirm that all of the model parameters can be estimated simultaneously using the NPFSI estimator and still result in a valid 2-DOF model.

The reduced-order NPFSI estimator is therefore applied across the entire range of operation simultaneously at 3 values of $\varepsilon$, in order to simultaneously estimate the 4 model parameters. The results are provided in table III.
Fig. 7. Measured and theoretical equilibrium $i_d$ currents at each air-gap.

Fig. 8. Comparison between various estimates of $L_1(g)$.

The comparisons show that the model generated using the full-span NPFSI estimator describes the behavior of the system to a reasonable degree of accuracy over the desired air-gap range. It should be noted that the horizontal dynamics produced by the 2-DOF calibration procedure appear to diverge from what was estimated in the fixed air-gap case. This indicates that the decoupled estimates may be more accurate or that there was not sufficient persistency of excitation. As a result, elements of both the full parameter estimator and the fixed air-gap estimator will serve as the 2-DOF calibration procedure in future control experiments.

VI. CONCLUSIONS AND FUTURE WORK

The model verification results in this paper have shown that when a calibration procedure derived from the work presented in [4] is applied to a realization of a PMLSM-based 2-DOF magnetic levitation system, the state-space model from (1) can accurately predict the behavior of the physical system in an air-gap range between 15 and 25 mm and an horizontal range between $-50$ mm and $50$ mm.

For air-gap values any smaller then the 15mm limit, the effects of uncertainties such as the cogging force become significant and require representation within the modelling.

These results show promise for the remaining part of the work which entails implementing the nonlinear control design developed in [3] on the 2-DOF device presented here as well as on a 3-DOF device under construction.

VII. ACKNOWLEDGMENTS

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REFERENCES