A Position Estimator Using Kalman Filter With a Data Rejection Filter for a Long-Stator Linear Synchronous Motor of Maglev

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ABSTRACT As a maglev levitates with a small air gap and runs very fast, securing the levitation system’s stability is crucial. Thus, the high-performance decoupling control between the propulsion control system and the levitation system is of critical importance. The study described in this paper focuses on a high-performance position estimator that minimizes the dynamic coupling between the levitation system and propulsion system in a maglev’s propulsion control system using a long-stator linear synchronous motor. To that end, a position estimator using a Kalman filter was designed. Then the stability of the designed filter and its characteristics and problems that result from the change in the measurement covariance value were identified through a stability analysis of the Kalman filter. Moreover, in an attempt to improve it, a Kalman filter with a data rejection filter was proposed. Afterward, to verify the performance of the proposed position estimator, a maglev train model was fabricated and for each Kalman filter measurement covariance value, the dynamic coupling between the propulsion control system and the levitation system was identified through the test. For the Kalman filter using a data rejection filter, it was confirmed that the propulsion control system could minimize the influence on the levitation system when an inaccurate position of the vehicle is renewed.

INDEX TERMS Influence of electromagnetic suspension system, Kalman filter, long stator linear synchronous motor, maglev, position estimation techniques.

I. INTRODUCTION
Considering their speed, reliability, environmental impact and safety, maglev trains can potentially be the optimal transit solution [1], [2]. In an electromagnetic attraction system, a long-stator synchronous linear motor (LSLSM) serves as the propulsion system of vehicles. The stator packs are attached to the guideway, and the support magnets attract the vehicle to the guideway from below. A highly reliable electronic system ensures that the vehicle always remains at a uniform distance of 10 mm above the guideway [3].

The thrust and levitation force control of the LSLSM is a key point in evaluating the performance of the maglev train [4]. Therefore, high-performance decoupling control between the thrust and normal forces in LSLSMs for maglev systems is required [5], and when it is satisfied, the safety and stable operation of magnetic levitation trains are possible. It was proven that a 90° phase angle between the armature current field and the magnetic field produced by the levitation magnets is helpful for decoupling the thrust and normal forces [6], [7]. To control the phase angle to be 90°, precise position information is required, however, the maglev propulsion control system is equipped with low-resolution positioning sensors. Therefore, position estimation techniques, such as the Lagrange interpolation method or position observer method, have been developed to estimate the precise required position based on the measured position [8], [9]. However, position estimators that use the Lagrange interpolation method continuously estimate the position when an inaccurate position of the vehicle is renewed, and the position estimator method that uses the full-order observers provides smooth estimates of the actual position, but in noisy environments, the observer may fail to find a stable position. Such errors in the estimated position tend to reduce the thrust force of the thrust system.
and generate external forces on the levitation system, resulting in significant performance degradation of the levitation gap control [7], [10]. In [11], a speed estimator using a Kalman filter was proposed to obtain the instantaneous position and speed of the machine under the measurement noise in the position sensors due to the encoder, and the estimator was proven to exhibit a good performance in the presence of a coarse position measurement quantization. However, when the measuring position changes in a stepwise manner, e.g., when the measuring position is missed because of a communication failure or measurement failure of the positioning systems, it typically generates the wrong position and/or phase delay and influences the levitation gap control, leading to overall deterioration of the performance of the levitation control system.

In this paper, we propose a position estimator that uses a Kalman filter with a data rejection filter. With the aid of the data rejection filter, the proposed Kalman filter position estimator can operate without significant performance degradation, even if the transmitted position is missed or distorted. This paper is organized as follows:

In Section II, the interaction between the propulsion system and the levitation system due to the measurement position error is described. In Section III, the principle of the position estimator that uses a Kalman filter with a data rejection filter is presented, and through the stability analysis of the Kalman filter, the pole location of the various measurement noise covariances in the s-domain is shown and analyzed. In Chapter IV, the specification of a miniature maglev is described and experimental results summarized. Finally, the summary of this paper is provided in Section V.

II. INTERACTION BETWEEN THE LEVITATION SYSTEM AND PROPULSION SYSTEM

The decoupling control strategy of the LSLSM is based on the d-q axes coordinates. Equations (1) and (2) give the voltage equation of the LSLSM

\[ u_d = r_s i_d + \frac{\pi U_m}{\tau} \Psi_d + \frac{d}{dt} \Psi_d \]

\[ u_q = r_s i_q + \frac{\pi U_m}{\tau} \Psi_q + \frac{d}{dt} \Psi_q, \]

where \( u_d \) and \( u_q \) indicate the voltage on the d- and q-axis, respectively. When the power phase is \( \delta \), \( u_d = U \sin \delta \), and \( u_q = U \cos \delta \), where \( U \) indicates the stator voltage amplitude; \( r_s \) is the resistance of the stator winding; \( i_d \) and \( i_q \) are the current on the d-q axes, respectively; \( \tau \) is the pole pitch; \( U_m \) is the mover’s travel speed; and \( \Psi_d \) and \( \Psi_q \) are the flux linkage on the d-q axes, respectively.

The equation for the flux linkage is as follows:

\[ \Psi_d = i_d \times (L_{\sigma} + L_{md}) + i_f \times L_{md} \]

\[ \Psi_q = i_q \times (L_{\sigma} + L_{mq}), \]

where \( L_{\sigma} \) indicates the stator leakage-inductance; \( L_{md} \) and \( L_{mq} \) are the main-inductance of the d- and q-axis, respectively, where \( L_d = L_{md} + L_{\sigma} \) and \( L_q = L_{mq} + L_{\sigma} \); and \( i_f \) is the converted current on the stator side of the second pole.

The electromagnetic thrust can be expressed as

\[ F_x = \frac{3\pi}{2\tau} (\Psi_d i_q - \Psi_q i_d) \]

\[ = \frac{3\pi}{2\tau} L_{md} i_f i_q + \frac{3\pi}{2\tau_t} (L_{md} - L_{mq}) i_d i_q \]

(5)

The attraction force between the stator and levitation magnets can be expressed as [10]

\[ F_x = \frac{3}{2} \left[ l_d \frac{d\Psi_d}{dg} + i_d \frac{d\Psi_d}{dg} \right] \]

(6)

where \( \frac{d\Psi_d}{dg} \) and \( \frac{d\Psi_q}{dg} \) indicate the d- and q-axis derivatives of the flux linkage with air gap \( g \), respectively.

The levitation force of the motor is as described in (7) below:

\[ F_x = \frac{3}{2} \left[ (i_d + i_f) \frac{1}{g} L_{md} + i_d^2 \frac{L_{mq}}{g} \right] \]

(7)

In the rotor field oriented control, a synchronous rotation axis is aligned with the phase of the rotor phasor. However when a phase lag occurs, as in Fig. 1, it works according to the axis \( d \rightarrow q \). In fact, the axis \( d \rightarrow q \) is ahead by \( \Delta \theta_m \). Thus, an interaction between the stator current and the magnetic flux of the rotor occurs.

Based on the above analysis, (5) and (7) were developed into (8).

\[ F_x = \frac{3\pi}{2\tau_t} (L_{md} i_f i_\cos \Delta \theta_m) \]

\[ + \frac{3\pi}{2\tau_t} (L_{md} - L_{mq}) i_f^2 \sin \Delta \theta_m \cos \Delta \theta_m \]

(8)

\[ F_x = \frac{3}{2} \left[ i_\Delta \theta_m + i_f \right]^2 \frac{L_{md}}{g} + i_\cos \Delta \theta_m \frac{L_{mq}}{g} \]

From (8), we can see that the lagged phase angle \( \Delta \theta_m \) has a harmful effect on the propulsion system; it reduces the thrust force and changes the levitation force.

III. PRINCIPLE OF THE POSITION ESTIMATION OF THE KALMAN FILTER WITH A PROPOSED DATA REJECTION FILTER FUNCTION

A. ESTIMATION OF THE POSITION AND SPEED USING A KALMAN FILTER

A maglev vehicle, such as the TR maglev system, detects the absolute position value and transmits it to a ground propulsion inverter at 20 ms intervals. This is not compatible with the requirements of a real-time propulsion control system, which should control the current at 1-2 ms intervals. Thus, the LSLSM-based propulsion control system requires a high-precision linear position estimator [8]. A Kalman filter is a state estimator that can practically produce optimal estimates, and it is usually applied to dynamic systems that involve random noise environments [11]. Thus, the Kalman filter is a suitable choice for estimating the instantaneous position of a train in the presence of a very coarse position measurement quantization due to the low-resolution position-sensing systems.

where the position estimator is as follows [11]:

\[
\begin{align*}
\dot{x} &= Ax + Bu + Bw \\
y &= Cx + u,
\end{align*}
\]

(9)

where

\[
A = \begin{bmatrix}
0 & 1/D_{em} & 0 \\
0 & -1/M_v & 0 \\
0 & 0 & 0
\end{bmatrix}, \quad B_1 = \begin{bmatrix}
0 \\
1/M_v \\
0
\end{bmatrix},
\]

\[
B_2 = \begin{bmatrix}
0 \\
0 \\
1
\end{bmatrix}, \quad C = \begin{bmatrix}
1 & 0 & 0
\end{bmatrix}, \quad x = \begin{bmatrix}
\theta_m \\
v_m \\
\tau_d
\end{bmatrix}^T.
\]

The input variable is the torque reference value \( u \) and the state variables include the mover’s angular position \( \theta_m \), mover’s velocity \( v_m \), and the disturbance load torque \( \tau_d \). The output variable \( y \) is the mover’s angular position \( \theta_m \), and \( T_N \) is the rated torque of the LSLSM.

Both \( w \) and \( u \) are represented as follows:

\[
w = \begin{bmatrix}
u_{noise}
\end{bmatrix}, \quad u = \theta_{noise},
\]

(10)

where \( u_{noise} \) is the process noise in the control input, \( \theta_{noise} \) is the process noise in the disturbance load torque, and \( \theta_{noise} \) is the measurement noise in the position signal from the mover.

The process noise \( \tau_{noise} \) comes from the A/D converter in the controller and the measurement error of the current sensor, and the position measurement noise comes from unstable measurements caused by vehicle shaking, communication errors or other reasons. Therefore, the variance matrix of the process noise vector \( Q \) and the variance matrix of the measurement noise vector \( R \) are written as

\[
Q = \begin{bmatrix}
q_0 & 0 \\
0 & q_1
\end{bmatrix}, \quad R = [r_1]
\]

(11)

where \( q_0 \) is the torque reference covariance value, \( q_1 \) is the disturbance torque covariance value, and \( r_1 \) is the measurement covariance value.

As the zero-order-hold method is used, (9) can be discretized as [12]

\[
x_k = \Phi x_{k-1} + \Gamma u_{k-1} + Gw_k \\
y_k = Hx_k + \nu_k,
\]

(12)

(13)

where

\[
\Phi = e^{A\tau}, \quad \Gamma = \int_0^{T_s} e^{A\tau} B_1 d\tau,
\]

\[
G = \int_0^{T_s} e^{A\tau} B_2 d\tau, \quad H = C
\]

When the sampled data system is considered, the measured noise \( \nu_k \) maintains the same variance, and the sampled process noise \( w_k \) can be represented by the following co-variance matrix [12]:

\[
Q_k = \int_0^{T_s} e^{A\tau} B_2 \begin{bmatrix}
q_0 \\
0
\end{bmatrix} B_2^T e^{A\tau} d\tau
\]

(14)

The Kalman filter process for this system can be given by the following equations:

estimation:

\[
\hat{x}_k = \Phi \hat{x}_{k-1} + \Gamma y_k - \nu_k
\]

(15)

update:

\[
P_k^+ = \Phi \hat{x}_{k-1} P_{k-1} \Phi^T + Q_k - \nu_k
\]

(16)

(17)

\[
P_k = (I - K_k H_k) P_k^+
\]

(18)

where \( P_k^+ \) is the prediction error covariance matrix at time \( k \) and \( P_k \) is the estimation error covariance matrix.

**B. ANALYSIS OF THE CHARACTERISTICS FOR THE \( R_k \) CHANGE THROUGH AN ANALYSIS OF THE KALMAN FILTER STABILITY**

The dynamic stability of a system usually refers to the behavior of its state variables. If the actual measurement processing in the Kalman filter state equations were neglected, the resulting equations would characterize the dynamic stability of the filter itself [13]. In the continuous case, these equations are as follows:

\[
\dot{x} = (\Phi(t) - K(t)H(t))x(t)
\]

(20)

Fig. 2 presents the location of the roots at the s-domain for the position estimator using the Kalman filter. In this analysis, the measurement covariance value \( R_1 \) in (11) was chosen to be 0.01, 0.05, and 0.1, respectively. From Fig. 2, we can see that all the poles are located in the left half of the plane, which means that the position estimator is stable. In this figure, as the value of the measurement noise covariance increases, the location of the poles is moved to an imaginary axis, which means that the filter bandwidth can be narrowed by reducing the weighting of the measured value.
Thus, the measurement noise was effectively removed by increasing the measurement noise covariance value, but the response of the position estimator was more sluggish. Consequently, the position error at the transient state decreased, whereas the transient state time increased, which means that a significant mutual interference between the propulsion system and the levitation system occurs during long transient periods owing to the phase lag of the estimated value.

On the other hand, when reducing the measurement noise covariance value $R_k$, the transient state time decreased while the position error at the transient state increased, which means that large disturbances in the levitation control system occur during short transient times.

C. DESIGN OF THE POSITION ESTIMATOR OF THE KALMAN FILTER WITH A DATA REJECTION FILTER

Propulsion systems require decoupling control between their thrust and levitation forces to generate a stable thrust force. However, maglev trains use the noncontact method to detect their positions. Therefore, the position signals sent by the position sensors are usually aberrant and noisy because of vibrations or instrument faults. Furthermore, the measured values often jump when the trains pass a guideway rail joint or when the position detection system has an operation problem [14]–[17].

If the measurement covariance value $R_k$ in a position estimator that uses a Kalman filter increases, the estimated error resulting from the measurement error, such as a phase-angle jump at the transient state, diminishes. However, the estimation results can have time delays for long durations. To address this phenomenon, the measurement covariance value $R_k$ must be decreased. In such a case, however, the estimation error increases for a short time.

Discrete linear filters can be effectively used to reduce the effects of some of the state variables to the point that they can be safely ignored. Thus, if adequate information on the innovation vector $[y_k - H_k \hat{x}_k]$ exists, nonlinear “data rejection filters” can be implemented [13]. Therefore, the data rejection filter technique was applied to the Kalman filter to minimize the effects resulting from measured position jumps.

In (18), the difference between the measurement value $(y_k)$ and the state prediction value $(H_k \hat{x}_k)$ indicates the $i$th noise element of $\nu_k$ in (13). This implies that the noise element is profoundly affected by the measured position jump if the difference is larger than the given boundary value $\varepsilon$ in (21). Therefore, the measured value is discarded because it is heavily distorted. As the measured value is replaced by the process value, it does not have any effect on the calculation of a posteriori state vector $\hat{x}_k$ [18].

$$|y_k - H_k \hat{x}_k| \geq \varepsilon$$  \hspace{1cm} (21)

Fig. 3 presents the flowchart of the Kalman filter algorithm with a data rejection filter.

In [18], the threshold value uses a predetermined value. However, in the case of a vehicle moving at high speed, the error of the measured value tends to increase in proportion to the vehicle speed. Therefore, it is desirable to increase the threshold value as the speed increases. Thus, the threshold value $\varepsilon$ in this paper is represented by (22).

$$\varepsilon = 50\% \times \tilde{v}_m \times T_s,$$  \hspace{1cm} (22)

where $\tilde{v}_m$ is the estimated speed of the vehicle and $T_s$ is measurement position update time.

The data rejection filter was applied when the vehicle’s speed was greater than 0.5 m/s to avoid malfunctions at low speeds, and the value of $\varepsilon$ was set at approximately 50% of the traveled distance for a position update cycle time.

IV. TEST RESULTS

The test device is a scale model test device designed to test the propulsion control algorithm before developing a full-scale maglev train. The system comprises a 120-kg system.
model maglev that runs along a 10-m-long guideway and a modular inverter-based propulsion control system to drive the train. The maglev vehicle model has two four-pole electromagnets for levitation and four electromagnets for guidance. Fig. 4 presents the test apparatus, which comprises a maglev vehicle model and a multilevel inverter.

Table 1 presents the specifications and parameters of the test device.

Table 1. Specifications of the model maglev vehicle and propulsion system.

| Category          | Parameter                  | Small Maglev & 5-Level Inverter |
|-------------------|----------------------------|---------------------------------|
|                   | Mass of Secondary mover    | 120(kg)                         |
|                   | Number of Levitation Magnets | 2                               |
|                   | Number of Poles            | 4                               |
| Secondary Mover   | Pole Width                | 0.025(m)                        |
|                   | Slot Width                 | 0.028(m)                        |
|                   | Number of Guidance Magnets | 4                               |
| Long Stator       | Length of Stator (per unit)| 1.7(m)                          |
|                   | Armature resistance        | 5.9(Ω)                          |
|                   | d-axis Inductance          | 40.0(mH)                        |
|                   | q-axis Inductance          | 38.6(mH)                        |
|                   | Pole Width                 | 0.02(m)                         |
|                   | Slot Width                 | 0.02(m)                         |
| System            | Thrust Constant            | 4.5(N/A)                        |
|                   | Operating Air-gap          | 3.5(mm)                         |
|                   | Length of Guideway         | 10.3(m)                         |

was used as the main control chip to drive the proposed control algorithm.

The air gap value and the electromagnet current value measured by the mover are transmitted to the ground database by a radio system through the vehicle’s DAQ system. Also, various control variables and measured values, such as $i_u$, $i_v$, and $i_w$, in the ground inverter are stored at the scope coder through the D/A converter. The propulsion inverter was designed to operate in reactor mode by connecting the contactor $K_1$ at low-speed operation and in the transformer mode by connecting the contactor $K_2$ under high-speed operation. The position signaling measured by the vehicle’s barcode is transmitted to the ground propulsion system through wireless LAN and CAN communication.

Fig. 6 presents the gain and phase response of the magnetic suspension system for different frequencies. According to the test results, the bandwidth of the levitation air gap controller is 8 Hz or more. Thus, when the levitation air gap is changed or when there is an external force by the LSLSM, it responds quickly, within about 100 ms.

The test conditions in Figs. 7–11 are as follows. With a levitation air gap of approximately 4 mm, a q-axis current of 13 A was constantly supplied to the LSLSM electromagnet for operation, and the position value measured by the vehicle was transmitted to the ground propulsion inverter at a certain interval. In addition, the measured value was designed to jump at certain locations to identify the characteristics of the LSLSM and the levitation system depending on the error of the position estimator. The position update cycle was set at 20 ms to avoid any difficulties in vehicle operation when not using a...
position estimator, but it is normally set at 40 ms to accurately identify the characteristics of the position estimator.

Figs. 7(a)-10(a) present the estimated vehicle speed $\tilde{v}_m$, phase angle of the measurement position $\theta_m$, phase angle of the estimated position $\theta_e$, and stator current $i_u$, and Figs. 7(b)-10(b) show the levitation air gap of each vehicle $\text{Gap}_1$ and levitation electromagnet current $i_{\text{mag}1}$.

Fig. 7 presents the waveform of the stator and mover in response to the phase-angle jump when operating at a q-axis current of 13 A. In Fig. 7(a), the measured position value is transmitted at a cycle of 20 ms. In addition, at a certain section (3.1-3.4 s) where the position information was not constantly transmitted, the current temporarily had a DC value. Then, as presented in Fig. 7(b), the magnetic coupling from the levitation air gap and the current occurred between the LSLSM and the levitation magnet, which led to a significant variation in the air gap.

Fig. 8 presents the case in which a position estimator was used with the Kalman filter when the measurement covariance value $R_k$ was set at 0.01. At the measurement position of the jump section (3.3-3.5 s) in Fig. 8, the Kalman filter produced a position estimate value that was severely distorted owing to the excessive amplification of the position error, and it took a transient time of approximately 600 ms to reach the normal state after correcting the position value.

Fig. 8(b) presents the air gap variation in the levitation system due to the variation in the LSLSM’s attraction force when the position estimate value of the Kalman filter was severely distorted owing to the excessive amplification of the position error.

The phase angle of the position estimator lagged by 1.2 rad/s in comparison with the measured phase angle, which
resulted in a reduction in the attraction force that influenced the levitation system, which means that the levitation air gap during the transient time increased. Thus, the levitation current also increased and then decreased back to its normal value.

Fig. 9 shows that the measurement covariance value $R_k$ was set at 0.1, which was increased by 10 times to reduce the weighting of the measured value. At the measurement position of the jump section (2.7-2.9 s), as presented in Fig. 9(a), the position estimator using the Kalman filter was able to estimate a relatively linearized position in comparison with Fig. 8(a), and the LSLSM’s electromagnetic current appeared to be more sinusoidal. However, the transient time required by the position estimator to reach the normal state after restoring the measured value to the normal value was approximately 100 ms, and the maximum phase-angle lag was found to be 1.64 rad/s, which indicates that a reduction in speed occurred owing to the variation in the thrust force. Also, at this time, there were significant changes in the levitation air gap and current, as presented in Fig. 9(b).

Fig. 10 presents the case in which the position estimator used the Kalman filter with a data rejection filter, and the measurement covariance value $R_k$ was set at 0.01 to rapidly follow the measurement value, as observed in Fig. 8. Fig. 10(a), from the top to bottom, presents the graph of the vehicle’s estimated speed $\tilde{v}_m$, the deviation between the measurement position and the estimated position $S_{err}$, phase angle of the measurement position $\theta_m$, phase angle of the estimated position $\theta_e$, and stator current $i_s$. Further, Fig. 10(b) presents the levitation air gap of each vehicle $Gap_1$ and the levitation magnet current $i_{mag1}$.

When the error between the measured position and the estimated position exceeded the value $\varepsilon$ at the measurement position of the jump section (4.7-4.9 s), as presented in Fig. 10(a), the transmitted position value was rejected. Then, the value estimated using the Kalman filter was adopted to estimate the position in the next step. This enabled us to discover that the vehicle’s speed increased even under the same conditions. As only a slight variation in the attraction force by the LSLSM affected the levitation system, no signif-
icant variation in the vehicle’s air gap and levitation current occurred, as observed in Fig. 10(b).

Fig. 11 presents a schematized RMS value of a real-time levitation air gap and a levitation current using the toolbox of Matlab/Simulink to analyze the air gap and current in Fig. 8(b)-10(b). In Fig. 11, when the measurement covariance value $R_k$ was 0.01, a measured position jump occurred and a significant instantaneous air gap variation RMS appeared, but the transient time was short. When $R_k$ was 0.1, a relatively smaller change in the estimated position occurred for a significant position error, and the transient time was longer.

In the case of the Kalman filter with the data rejection filter, the estimated speed was unaffected by the measurement position of the jump section, and no other changes were observed. Thus, precise position estimation by the proposed position algorithm was deemed possible, and the interference of the propulsion system with the levitation system was minimized, relatively reducing the RMS value of the levitation air gap. As mentioned earlier, minimizing the RMS value of the levitation current would improve the stability and quality and prevent the deterioration of the levitation magnet due to the reduction in the levitation magnet current.

Fig. 12 presents the test results of the propulsion system using a Kalman filter with a data rejection filter, and Fig. 13 presents the estimated performance when the measurement position update cycle of the Kalman filter is extended to 80 ms.

The results demonstrated that the Kalman filter with the proposed data rejection filter provided superior position estimation performance even when the measured position update period was longer. Thus, the proposed Kalman filter with the data rejection filter proved to be the optimal algorithm for maglev applications.

V. CONCLUSION

In this paper, a study on a position estimator that can effectively deal with position information errors was conducted to enhance the stabilization and propulsion efficiency of the propulsion systems of maglev trains.

The relationship between the levitation force and the variation in the propulsion force of an LSLSM was reviewed based on an interaction formula, and an optimal position estimator using a Kalman filter was designed to achieve high-precision linear position detection in propulsion control systems. In addition, the problems with a position estimator using a Kalman filter in dealing with the excessive amplification of the position errors, such as the measurement position of jump sections, were analyzed, and a Kalman filter that used a data rejection filter to address such problems was proposed.

According to the test results, the proposed position estimator proved to be sufficiently stable in dealing with position jumps, and it provided accurate linear position information during normal operation. Moreover, it could improve the propulsion efficiency of the propulsion system and the dynamic stability of a magnetic levitation system.

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