Precise External Force Estimation of Helical Motors using Magnetic-attractive-force Error Compensation

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This paper presents the external force estimation for helical motors contain the magnetic levitation system. The helical shape of helical motors induces a wide inductive gap; thus, their thrust density is 1.5 times higher than that of general cylindrical linear motors. Furthermore, by magnetically levitating the mover, the motor can be directly driven. However, owing to the variations in the magnetic attractive force acting on the mover, the accuracy of external force estimation is lower than that of cylindrical motors. To solve this problem, this study proposed the combination of the thrust and torque disturbance observers of this motor for external force estimation irrespective of the magnetic attractive force. Numerical simulations and experimental results demonstrated that the proposed method can achieve the highest precision.

Keywords: helical motor, external force estimation, two-mass system

1. Introduction

A human-robot interaction system has attracted attentions because it can provide labor force in industry, healthcare and other fields [1]. Hence, the safety of the interaction system has been strongly required, and it has been studied to introduce the precise force/torque detection or the mechanical elastic elements [2, 3]. Although load-cell, strain-gauge and other sensors can measure the force or torque precisely, these are expensive and require enough installation space. For these reasons, it is often undesirable to use these sensors. Thus, the external force or torque estimation methods have been developed for various actuators. As one of the actuators, there is Direct-Drive (DD) motor that consists of only an electric motor. It has wide control bandwidth and large output force/torque although the size is larger than the others. Since this actuator does not combine any mechanical gears, it has only slight frictions and can get high back-drivability. Hence, using only the motion equation of the motor, it is possible to estimate the external force/torque [4].

On the other hand, to increase the thrust density of a linear DD motor, the authors have developed helical motor [5–7]. This motor has a helical mover and stator where permanent magnets and two three-phase windings are installed, respectively. Thanks to the helical shape, this motor can get wider inductive gap area than a general cylindrical linear motor. In facts, the rated thrust density per effective volume of the second and third prototype is over 194 kN/m³ (60N) and 956 kN/m³(100N), the value is about 1.9 and 8.5 times higher than shaft motors having 60N and 113N rated force, respectively. Furthermore, since the magnetic levitation of the mover is conducted and the motor is almost free from the mechanical friction, this motor is backdrivable. The high backdrivability has been examined from the experiments of the force-sensorless control [6]. This motor is a two-mass system consists of the thrust and torque equations that the coupling is made by the magnetic attractive force. Due to that, the magnetic attractive force error strongly affects to the external force estimation accuracy. In the last studies, identifying the offset error and the nonlinearity of the magnetic attractive force, the error has been suppressed. However, since the magnetic attractive force variation depends on the manufacturing accuracy and others, it is necessary to develop an external force estimation of the helical motor that is accurate regardless of the magnetic attractive force error. On the other hand, the other two-mass systems such as series elastic actuators have also the external force estimation error caused by the coupling or torsion force. For solving this issue, Multi-Encoder Disturbance Observer (MEDOB) [8], a residual-based estimation [9,10], and others have been proposed. MEDOB consists of an equation combining the primary- and secondary-side motion equation. Thanks to this, it can remove the torsion force term from the estimation. Hence, using the combined equation, the primary-side input-and-output and the secondary-side output information, it is possible to estimate the external force without the torsion force/torque. To improve the robustness of the MEDOB, Yamada, et al. have combined a load-side observer to this [11]. Meanwhile, the residual-based estimation has the two-staged estimation structure: the first stage is the torsion force estimation, and the second is the external force estimation using the estimated torsion force. Consequently, the accuracy of the MEDOB and the residual-based estimation is regardless of the torsion force variation. The requirements of both methods is the primary side input/output and the secondary side output sensors for the two-mass system. Even though both methods have the utility, the output sensors ac-
accuracy of the primary and secondary should be identical on the combined equation. If the sensors have different accuracy, the difference causes the estimation noises/errors.

To solve this issue, this paper presents an external estimation method combining the primary- and secondary-side DOB with the different cutoff-frequency for the helical motor. Combining the DOBs, the estimation not only can apply the suitable cutoff frequency for each sensor, but also can suppress the estimation error caused by the magnetic attractive force variation.

2. Helical motor

2.1 Mechanical structure The prototype of Interior Permanent-Magnet (IPM) type of the helical motor is shown in Fig. 1. The both of mover and stator are helical shaped [6]. The mover and stator has the slots for installing the permanent magnets and two three-phase windings, respectively. By the electromagnetic and the magnetic attractive force, the mover can perform magnetic levitation. Thus, this motor has slight frictions as same as the general linear motors and can get high back-drivability. Besides, thanks to the helical shape, this motor can get wider inductive gap area than the general linear motors that have the cylindrical mover and stator. The thrust density per effective-volume of the helical motor is several times greater than the linear motors. By these characteristics, the advantages of this motor are high thrust density compared with the conventional linear motor, and the back drivability.

The gap displacement $x_g$ between the mover and stator is defined as (1).

$$x_g = x - \frac{l_p}{2\pi} \theta$$  \hspace{1cm} (1)

where $x$ is the linear position of the mover, $\theta$ is the mechanical angle of the mover, and $l_p$ is the lead length of the screw.

2.2 Modeling To get the motion model of helical motor, it is necessary to firstly derive the voltage equations. The voltage equation has been derived from the magnetic equivalent circuit [5]. Then, the thrust and torque of the motor are derived as (2)–(3) and (4)–(5) from the magnetic co-energies, respectively. Here, for simplification, the magnetic saturation of the mover and stator yoke is neglected.

$$f_1 = \frac{1}{l - x_g} (\Psi_{f1} i_{d1} + \frac{L_d i_{d1}^2 + L_q i_{q1}^2 + L_f i_{f1}^2}{2})$$  \hspace{1cm} (2)

$$\tau_1 = p(\Psi_{f1} i_{d1} + (L_d - L_q) i_{d1} i_{q1}) - \frac{l_p}{2\pi} \frac{1}{l - x_g} \left( \Psi_{f1} i_{d1} + \frac{L_d i_{d1}^2 + L_q i_{q1}^2 + L_f i_{f1}^2}{2} \right)$$  \hspace{1cm} (3)

$$f_2 = -\frac{1}{l + x_g} (\Psi_{f2} i_{d2} + \frac{L_d i_{d2}^2 + L_q i_{q2}^2 + L_f i_{f2}^2}{2})$$  \hspace{1cm} (4)

$$\tau_2 = p(\Psi_{f2} i_{d2} + (L_d - L_q) i_{d2} i_{q2}) + \frac{l_p}{2\pi} \frac{1}{l + x_g} \left( \Psi_{f2} i_{d2} + \frac{L_d i_{d2}^2 + L_q i_{q2}^2 + L_f i_{f2}^2}{2} \right)$$  \hspace{1cm} (5)

where $L_f$ is a self-inductance of equivalent field magnet windings, $L_d$ and $L_q$ are dq-axis inductances, $\Psi_f$ is an interlinkage flux from the permanent magnets to each windings, $l$ is the nominal air-gap length, $f$, $\tau$ are thrust and torque, and $i_d, i_q$ are the dq-axis currents. The subscript $k = [1, 2]$ corresponds to the forward and backward side.

From (2)–(5), the thrust and torque act on the mover are derived as follows.

$$M\ddot{x} = pq (f_1 + f_2) - D_x \dot{x} - f_{ex}$$  \hspace{1cm} (6)

$$J\ddot{\theta} = pq (\tau_1 + \tau_2) - D_\theta \dot{\theta}$$  \hspace{1cm} (7)

where $D_x$, $D_\theta$ are viscous friction coefficients of the linear and rotary motion, respectively. $p$ is a number of pole pairs per one layer, $q$ is a number of the mover layers, and $f_{ex}$ is the external force to the mover.

2.3 Linearized model of helical motor For designing controllers, (2)–(5) are linearized by Taylor expansion around $x_g = 0$. Using two independent inverters, it controls the dq-axis currents to be $i_{d1} = -i_{d2}$ and $i_{q1} = i_{q2}$, respectively. As this result, the thrust and torque act on the mover can be represented by (8) and (9). Here, the viscous frictions are assumed to be enough small, because the frictions are caused by only the bearing supports the shaft.

Figure 1: The 2nd prototype of helical motor (IPM type).
\[ p(q_1 + f_2) = pq \left( \frac{2\Psi_{f0}}{I} + \frac{2L_{f0}I_f}{B} x_g \right) \]
\[ = K_I x_d + K_g x_g \]  
(8)

\[ p(q_1 + f_2) = 2p^2 q_\Psi I_{f0} - \frac{l_p}{B} \tau_{total} \]
\[ = K_I x_d - \frac{l_p}{B} (K_p x_g + K_I x_d) \]  
(9)

where \( L_{f0} \) and \( \Psi_{f0} \) are the self-inductance of equivalent winding and the interlinkage flux of the permanent magnet at \( x_g = 0 \). Then, the linearized motion model is derived as (10) and (11).

\[
M \ddot{x} = K_I x_d + K_p (x_y - x_g) - f_e \tag{10}
\]

\[
\dot{\theta} = K_I x_d - \frac{l_p}{B} \left( K_p x_g + K_I x_d \right) \tag{11}
\]

where \( K_I \) is the thrust constant [N/A], \( K_p \) is the magnetic attractive force coefficient [N/m], \( K_r \) is the torque constant [Nm/A] and \( x_g \) is the neutral equilibrium point in the gap [m].

Note that, although \( x_g \) is ideally zero, it has a variation caused by the manufacturing accuracy of the actual machine.

### 2.4 Motion Controller for Helical Motor

#### 2.4.1 Acceleration control

The acceleration controller is designed by replacing the accelerations and the d-q axis current in (10) and (11) by each reference. Thrust and torque disturbance observers are introduced to guarantee the robustness.

\[
\dot{\tau}^e_{\text{tb}} = \frac{1}{K_{ml}} \left( M_n \dot{x}^e - \dot{f}_d - K_p x_g \right) \tag{12}
\]

\[
\dot{\tau}^e_{\text{tb}} = \frac{1}{K_{m\theta}} \left( J_d \ddot{\theta}^e + \ddot{\tau}_d + \frac{l_p}{2\pi} \dot{\tau}^e_{\text{tb}} \right) \tag{13}
\]

\[
\ddot{f}_d = \frac{\omega_d}{s + \omega_d} (K_p \dot{x}^e - K_p x_g - s M_n \dot{x}) \tag{14}
\]

\[
\ddot{\tau}_d = \frac{\omega_d}{s + \omega_d} (K_r \dot{x}^e - \frac{l_p}{2\pi} \left( K_p \dot{x}^e + K_p x_g \right) - s J_d \ddot{\theta}) \tag{15}
\]

where \( \ddot{f}_d \) and \( \ddot{\tau}_d \) are the estimated thrust and torque disturbances, respectively. The subscript "tb" represents nominal values of the coefficients. Meanwhile, the rotary acceleration reference \( \ddot{\theta}^e \) is calculated from the linear and gap acceleration reference \( \ddot{x}^e \), \( \ddot{x}^g \) as shown in (16). The \( \ddot{x}^e \) and \( \ddot{x}^g \) are given by the position/force and gap controller.

\[
\ddot{\theta}^e = \frac{2\pi}{s} (\ddot{x}^e - \ddot{x}^g) \tag{16}
\]

#### 2.4.2 Power-saving magnetic levitation control

The magnetic levitation controller consists of PD control as shown in (17). The control gains are designed by the pole-placement of the transfer function between the gap response and reference.

\[
x^e_{\text{tb}} = K_p (x^e_{\text{tb}} - x_g) + K_d (x^e_{\text{tb}} - x_g) \tag{17}
\]

where \( x^e_{\text{tb}} \) is a gap reference that is given by zero-power control. In this paper, for reducing the copper loss caused by the magnetic levitation, the current integral zero power controller is implemented [7].

\[
x^e_{\text{tb}} = K_p \int \ddot{x}^e_{\text{tb}} dt, \quad \dot{x}^e_{\text{tb}} = K_d \ddot{x}^e_{\text{tb}} \tag{18}
\]

Here, \( K_I \) and \( K_d \) are gains of the zero-power controller.

#### 2.4.3 Force control

The acceleration of the linear motion \( \dot{x} \) can realize either the desired linear-position or thrust. Due to this, a calculation of the acceleration reference is switched by the control objective. When the thrust control is the objective, the reference is switched to P-control with the external or reaction force feedback.

\[
\ddot{x}^e_{\text{tb}} = K_p \left( f_{\text{cmd}} - f_e \right) \tag{19}
\]

where \( f_e \) is the estimated external force.

In this paper, the accuracy of the external force estimation of the helical motor is discussed, and more precise estimation method is proposed.

### 3. External force observer for the helical motor

#### 3.1 Conventional EFOB for the helical motor

In the latest study, the External Force Observer (EFOB) for the helical motor has been designed by using the thrust disturbance observer only (14). In the helical motor, the variation of the neutral point \( x_g \) under unloaded affects to the magnetic attractive force acting on the mover as \( K_p (x_y - x_g) \). To compensate the effect in the \( f_e \), the estimated neutral point under unloaded \( \dot{x}_g \) is introduced to the EFOB. Then, the conventional EFOB has been constructed as shown in (20).

\[
\dot{f}_e = \frac{\omega_d}{s + \omega_d} (K_p \dot{x}^e - K_p x_g - s M_n \dot{x}) \tag{20}
\]

The gap reference (18) converges to the \( x_g + f_e/K_p \) in the steady state. Owing to this, it can update the \( \dot{x}_g \) by using the gap reference \( x^e_{\text{tb}} \) while the external force is zero. Therefore, for the conventional EFOB, a discriminant is required to detect the no load state. Using the force reference and the dq-axis current, it has distinguished the state as follows. Variables with super script "th" represent the threshold values which are tuned by trial-and-error with taking each sensor noise into account.

\[
\text{if } \left\{ f_{\text{cmd}} = 0 \right\} \text{and} \left\{ \left| \dot{x}_g \right| < \dot{x}^e_{\text{th}} \right\} \text{and} \left\{ \left| \dot{x}_g \right| < \dot{x}^e_{\text{th}} \right\} \text{then}

\dot{x}_g = \dot{x}^e_{\text{th}}
\]

\text{end if}

Figure 2 shows the block diagram of the conventional EFOB. If the updating \( \dot{x}_g \) is not adequate caused by the wrong threshold values, the current sensor noises, and others, it causes the force estimation error. Even if the \( x_g \) estimation under unloaded is adequately done, the error occurs by the variation of \( x_g \) under load and the nonlinearity of \( "K_p" \) around the gap limit. Due to that, the observer should have the parameter map of \( K_p \) given from the model identification.
result to compensate the nonlinearity.

The transfer functions of the estimated external force is derived from the simultaneous equation. It is difficult to consider the boundary conditions in the transfer-function. Owing to this, the estimation error of $\tilde{\xi}_g$ is introduced to the equations as $\Delta_\xi g$. Additionally, to consider the observation noises of the linear and rotary motion, $\xi_s$ and $\tilde{\xi}_g$ are introduced to the motion equations. As these results, the transfer function from $f_{ex}$ to $\dot{f}_{ex}$ under the conventional EFOB is derived as (21).

$$\dot{f}_{ex}(s) = Qd(s)(f_{ex}(s) + K_q \Delta_\xi g(s) - Ms^2 \tilde{\xi}_x(s))$$  \hspace{1cm} (21)

(21) means that it is impossible to suppress $\Delta_\xi g$ by the conventional EFOB. In this paper, a combination of the thrust and torque DOB is proposed to solve this problem.

### 3.2 Proposed EFOB combines the torque DOB

This paper proposes the combination of the thrust and torque DOB to compensate the magnetic-attractive-force error caused by the variation of $x_g$ and $K_q$. The estimated values of the two DOBs are derived as (22) and (23).

$$\dot{f}_d = \frac{\omega_d(f_{ex} - K_q x_g)}{s + \omega_d} \hspace{1cm} (22)$$

$$\dot{\tilde{\xi}}_d = \frac{\omega_d(h K_q x_g)}{s + \omega_d} \hspace{1cm} (23)$$

From (23), the torque DOB can estimate only the magnetic attractive force caused by $x_g$. If $\omega_d$ equals to $\omega_d$, the sum of $\dot{f}_d$ and $\dot{\tilde{\xi}}_d/h$ equals to the external force $f_{ex}$ as (24).

$$\dot{\tilde{\xi}}_d = \dot{f}_d = \frac{\omega_d}{s + \omega_d} f_{ex} \hspace{1cm} (24)$$

In this case, the structure of this EFOB is equivalent to the one of DOB [8]. However, due to the cutoff frequencies of DOBs are identical, it is difficult to tune the complementary sensitivity function taking each sensor noise into account. Therefore, for the helical motors, this paper proposes the external force estimation combined the two DOBs as shown in Fig. 3. As the same manner of the (21), the transfer function of $f_{ex}$ is derived as (25). Here, the filters of DOBs (22) – (23) are represented by $Q_d$ and $Q_{\tilde{\xi}}$, and the observation noises $\xi_s$ and $\tilde{\xi}_g$ are introduced.

$$\dot{f}_{ex}(s) = Qd(f_{ex}(s) + (Q_d - Q_{\tilde{\xi}}) K_q x_g(s) - M Q_{\tilde{\xi}} s^2 \tilde{\xi}_x(s) - \frac{f_{ex}}{h} Q_{\tilde{\xi}} s^2 \tilde{\xi}_g(s)$$  \hspace{1cm} (25)

### 4. Simulations and experiments

#### 4.1 Simulation conditions

To discuss the validation of the proposed EFOB, it conducts an transfer function analysis using the linearized motion model under force-control and a numerical simulation using the nonlinear motion model. In this simulation, the feedback signal of the force controller is the measured external-force $f_{ex}$. The parameters of the controllers and the plant are shown in the Table 1.

### 4.1.1 frequency analysis

In this subsection, it compares the frequency characteristics of the MEDOB and the proposed EFOB on bode-plots. Here, the amplitude of the noises is normalized to be equivalent to 1um on the gap displacement. Hence, the observation noises $\xi_s$ and $\tilde{\xi}_g$ are given as impulse inputs of 1um and $1 \times 10^{-6}$/[h/(rad)], respectively. Then, it can get the frequency characteristics as shown in Fig. 4.

Under the ideal condition, MEDOB has no errors caused by $x_g$. However, it can confirm that the noise of the rotary motion sensor strongly affects to it from Fig. 4. Owing to this, it is difficult to increase the cutoff frequency. Contrary to this, although the proposed method has the error caused by $x_g$ in high frequency region, it is possible to suppress the complementary sensitivity. About the conventional method described in the section 3.1, the $x_g$ acts as the offsets, and the effect of the noise is equal to the led line in Fig. 4(b).
4.1.2 numerical simulation In this numerical simulation, MEDOB and Time-Varying Kalman Filter are introduced to compare the performance. To validate the compensation performance of the proposed EFOB, a $x_{g0}$ variation is introduced. Here, let us assume that the neutral point $x_{g0}$ in (8) and (9) changes depending on the linear displacement $x$. Thus, the $x_{g0}$ variation is supposed as (26).

$$x_{g0} = 0.1 \cos \left( \frac{\pi \cdot 0.1 \times 10^{-3} \cdot x}{1} \right) \ [\text{mm}]$$  \hspace{1cm} (26)

From Fig. 5(a) and (b), under $x_{g0}$ is static, the conventional EFOB can estimate the external force precisely. However, in Fig. 5(c) and (d), the method cannot update the estimated $x_{g0}$ under the load even if the $x_{g0}$ varies. On the other hand, combining the torque disturbance observer, the proposed EFOB can compensate the error caused by $x_{g0}$ regardless of the load state. To compare the accuracy and the computation cost of each method, RMSEs and the computation times are shown in Table 2.

Table 2: Comparison of RMSEs and computation time between each EFOB method in the numerical simulation Fig. 5(c) and (d). The CPU for the simulation is Intel i5-5200U @ 2.20GHz.

| Method   | RMSE of $f_{e1}$ [N] | RMSE of $x_{g0}$[mm] | Comp. time[us] |
|----------|----------------------|----------------------|----------------|
| Conv.    | 15                   | 0.125                | 0.48           |
| Prop.    | 0.74                 | 0.020                | 0.43           |
| MDEOB    | 1.27                 | 0.025                | 0.28           |
| KF       | 0.93                 | 0.025                | 0.80           |

In Table 2, the proposed method and Kalman-Filter have almost identical accuracy, but, the computation time of KF is about twenty times longer than the others. Although MEDOB has the shortest computation time, it is difficult to further increase the cutoff frequency owing to the differential noises of linear and rotary motions. The conventional method has the largest error since the updating is failed. Additionally, the computation time is not shorter than the others due to using the If-statement. Since the gap reference equals to $f_{e1}/K_{g}$ + $x_{g0}$ under the load, the conventional method cannot estimate $x_{g0}$ while $f_{e1}$ is not zero[N]. Thus, the compensation in the conventional method is stopped from 0s, and the large estimation error has occurred.

4.2 Experiments using the 2nd prototype This subsection shows the experimental results using the 2nd prototype (Fig. 1) to validate the performance of the conventional and proposed EFOB. The experimental setup and control parameters are shown in Fig. 6 and Table 3, respectively. Figure 7 shows the experimental results of the sensorless force-control using the conventional and the proposed EFOB.

From Fig. 7a and 7c, it can confirm the conventional EFOB has the large estimation error after the force command changed. On the other hand, the proposed EFOB can suppress the error as like the simulations. In Fig. 7d, from -2 to 0s, the estimated $x_{g0}$ is zero. This reason is that, in the experiment, after starting the magnetic levitation, the DOBs in the proposed EFOB have been reset once. About the accuracy difference between (b) and (d), the reason is that the estimated $x_{g0}$ did not change from 0s since the conventional method cannot update the $x_{g0}$ while the external force is not.
zero. On the other hand, since the proposed method can estimate it regardless of the load and force command conditions, it can yield the precise external force estimation.

5. Conclusion

This paper presents the study about the external thrust force estimation for the helical motor, and proposes the estimation method using the force/torque disturbance observers. From the simulations and experiments, it has confirmed that the accuracy of the proposed method is higher than the conventional method.

In future works, to suppress the differential noises of linear and rotary motion, the gain design should be more optimized. By this way, the method could be applied for general two-inertia systems. Hence, using other applications, the validation also should be done.

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