Study on Improving Overall Efficiency of Front-end Power Supplies by Employing Method of Surge Energy Recycling

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Keywords: front-end power supply, surge energy, recycling

In this paper, the authors propose a surge energy recycling converter. The proposed circuit is able to reduce the surge voltage of the secondary side and to recycle the surge energy, in a DC-DC converter stage of a conventional front-end power supply. Thus, the use of the low blocking voltage rectifier elements is possible, and the conduction loss is decreased. Further, the amount of surge energy that is wasted in a snubber circuit is decreased. As a result, the efficiency of the DC-DC converter stage is improved by about 1 percentage point.

Fig. 1 shows the configuration of a front-end power supply when using the proposed circuit. The input of the proposed circuit is connected to both ends of rectifier elements. The proposed circuit absorbs surge energy and reduces surge voltage applied to the rectifier elements. Furthermore, the proposed circuit recycles the absorbed surge energy.

Figs. 2 and 3 show the input and output power of the proposed circuit and the efficiency of the DC-DC converter stage, respectively. In Fig. 2, the output of the proposed circuit corresponds to the recycled surge energy. Thus, the efficiency of the DC-DC converter stage is improved, as shown in Fig. 3.

Fig. 4 shows the efficiency of the front-end power supply when the proposed circuit is used. It is proved that an efficiency of over 90% is possible at 20–100% load.

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**Fig. 1.** Configuration of a front-end power supply using a surge energy recycling converter

**Fig. 2.** Input and output power of the surge energy recycling converter

**Fig. 3.** Efficiency of the DC-DC converter

**Fig. 4.** Efficiency of the front-end power supply
Development of Motor Model of Rotor Slot Harmonics for Speed Sensorless Control of Induction Motor

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Keywords: induction motor, rotor slot harmonics, magnetomotive force, air gap length, vector control, fast fourier transform

A speed sensorless control method of an induction motor (IM) is proposed utilizing rotor slot harmonics (called slot harmonics for simplification). Since the slot harmonics are generated by the mechanical structure of IM, the control method is robust for parameter deviation.

In order to determine the stability domain and realize the control design of the speed sensorless control system utilizing slot harmonics, a mathematical model is necessary. Therefore, the purpose of this paper is to develop a mathematical dynamic model to represent not only steady-state but also transient-state characteristics of slot harmonics.

Slot harmonics voltage $v_{sh}$ that appears in a neutral point voltage is derived based on the three-phase model of the IM by taking into consideration the magnetomotive force harmonics and the change in the magnetic air gap caused by the rotor slots. The derived slot harmonics voltage $v_{sh}$ is represented as follows.

$$v_{sh} = \sqrt{2/3} \left[ Y_{ss} \cos(N_r \theta - \theta) \cdot i_{ds} + Y_{ss} \sin(N_r \theta - \theta) \cdot i_{qs} + Y_{sr} \cos(N_r \theta - \theta) \cdot i_{dr} + Y_{sr} \sin(N_r \theta - \theta) \cdot i_{qr} \right]$$

Here, $i_{ds}$ and $i_{qs}$ are d- and q-axis stator currents respectively, $i_{dr}$ and $i_{qr}$ are d- and q-axis rotor currents respectively, $Y_{ss}$ and $Y_{sr}$ are slot harmonics coefficients, $\omega$ is the stator angular frequency, $\omega_r$ is the rotor speed, $P$ is the time derivative ($d/dt$), and $N_r$ is the number of the rotor slot per pole pair.

$Y_{ss}$ and $Y_{sr}$ are identified according to the experimental results in which slot harmonics, magnetic flux and torque current are separated from each other according to the vector control of IM.

Fig. 1 shows the steady-state characteristic of $v_{sh}$. As shown in the figure, experimental values of slot harmonics voltage amplitude $V_{sh}$ and frequency $f_{sh}$ almost coincide with the corresponding calculated values $\hat{V}_{sh}$ and frequency $\hat{f}_{sh}$, where $V_{sh}$ and $f_{sh}$ are detected utilizing fast fourier transform. Fig. 2 shows the experimental and calculation results based on the variation in the load and velocity. As shown in the figure, the experimental results $v_{sh}$ and calculation results $\hat{v}_{sh}$ for load and velocity variation almost coincide with each other.

Therefore, the validity of the proposed model is verified by the steady-state and transient-state characteristics of slot harmonics voltage.

![Fig. 1. Experimental and calculation results of slot harmonics frequency and amplitude](image1)

![Fig. 2. Experimental (a) and calculation results (b) of slot harmonics waveform in transient state of rotational speed](image2)
System for Image-Processing-Based Inspection of a Screw Hole on a Molded Plastic Frame

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Keywords: screw hole inspection, pattern recognition, injection molding, multi camera, plural images

A screw hole is incorrectly molded if the pin on the mold is broken when the plastic is molded by injection molding. Sampling inspection is carried out manually to identify the incorrectly molded screw hole. In the sampling inspection, the incorrectly molded screw hole on the molded plastic frame is rarely overlooked. Therefore, the development of a system for the high-precision identification of the incorrectly molded screw hole is required.

The purpose of this study is to develop a screw-hole inspection system that distinguishes between a correctly molded screw hole and an incorrectly molded one. In this paper, a screw-hole inspection system is proposed. There is a need to capture clearly a screw hole on uneven plastic frame and therefore, a multi-camera system is used. The proposed system consists of several Web cameras with the individual adjustable focus. Moreover, the inspection of the screw holes is performed using an inspection algorithm that is developed for a multi-camera system.

The proposed inspection method of the shown in Fig. 1, is as follows. First, the center position of the screw hole in the captured image is centered in the proposed system. Next, the captured image is converted to a grayscale image and the grayscale image is converted to a binary image.

The correctly and incorrectly molded screw holes are distinguished on the basis of the counted number of pixels corresponding to screw hole in the binary image.

The experiment is performed as experiment is as follow. The purpose of this experiment is to verify that the center position of the screw hole is correctly identified and that the proposed system distinguishes the correctly molded screw hole from the incorrectly molded one.

Table 1 shows the accuracy of the inspection; the results indicate that the inspection accuracy of the proposed system is 100.0% the center position of the screw hole is correctly identified. Further, it is confirmed that the correctly molded screw hole is accurately from the incorrectly molded one. From the experimental result, the effectiveness of the inspection system is verified.

<table>
<thead>
<tr>
<th>Hole type</th>
<th>Accuracy of inspection (Correct number / Parameter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The correctly molded screw hole</td>
<td>100.0% (2548/2548)</td>
</tr>
<tr>
<td>The incorrectly molded screw hole</td>
<td>100.0% (2940/2940)</td>
</tr>
</tbody>
</table>

Fig. 1. The inspection flow

Table 1. The experimental results
Influence of High-Frequency Leakage Current on Motor Position Control in PWM Inverter-Fed Servo Drives

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Keywords: precision positioning, high-frequency leakage current, inverter current discontinuous mode

This paper shows that a high-frequency leakage current hampers precision positioning in PWM inverter-fed servo drives. The leakage current gives rise to several EMI issues. However, there is no report on the influence of the leakage current on motor position control.

Figure 1 shows an experimental system that can be used for measuring motor position variation. This system has a position control loop with a precise position sensor, the resolution of which is over one million per revolution. The power source is a single-phase 200 V AC source. The motor position $\theta_p$ is measured by a capacitance-type displacement meter once the motor positioning is completed. Figure 2 shows the measurement result for the motor position $\theta_p$. The motor position $\theta_p$ periodically varies about 3”, which corresponds to about 6 pulses of the motor position sensor. The variation frequency of 100 Hz is equal to twice the AC line frequency.

Several experimental results indicate that the position variation is related to the high-frequency leakage current circulating through the grounding system.

Figure 3 depicts a position control model of the servo drive system. The part in the dotted rectangle, which corresponds to the equivalent model shown in Figure 4, is simulated by PSpice, and the other part is simulated by MATLAB/Simulink. The cogging torque of the servo motor is taken into consideration, and it is assumed that the cogging torque varies with the rotor position.

Figure 5 shows a simulation waveform of motor position $\theta_p$. The variation frequency of 100 Hz is equal to twice the line frequency. This simulation result indicates that the leakage current affects the position control of the servo drive system.

The analysis result shows that the high-frequency leakage current affects the low-frequency motor position variation. Moreover, it is explained that the factors affecting the motor position variation are the high-frequency leakage current and inverter current discontinuous mode.
A Study on the Use of Shielded Cables in Inverter Output Wiring

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Keywords: common-mode current, shielded cable, grounding system, PWM inverter

An increasing number of voltage-driven-type PWM inverters have begun to be used recently for electrical equipment in buildings owing to energy conservation considerations. However, common-mode currents originate from this type of inverters, and problems due to such common-mode currents flowing in grounding systems of buildings have increased with their increased use. While it is necessary to study measures to overcome these problems by considering the entire circuit in question (since common-mode currents flow in the whole circuit including power-supply and grounding systems), there seem to have been very few such studies. In this study, the author constructed a test circuit comprising a PWM inverter, induction motor, and grounding electrodes, and he studied measures to suppress common-mode currents by using shielded cables and a grounding system.

Figure 1 shows the test circuit. Figures 2(a) and (b) show the results of measurement of common-mode currents in the case where the power supply cables were not shielded, and Figures 3(a) and (b) show the results of measurement of common-mode currents in the case where shielded cables were used as the power supply cables with the shielding grounded at the inverter-side end. From a comparison between Figures 2 and 3, we see that in the case shown in Figure 3, high-frequency currents in the megahertz band decrease slightly while low-frequency currents in the hundred kilohertz band increase. This indicates that the use of shielded cables causes common-mode currents of low frequencies to increase regardless of the grounding of the shielding. In contrast, high-frequency currents increase or decrease depending on the grounding of the shielding. Through measurements and the use of equivalent circuits, the author also studied the behavior of common-mode currents, and it became clear that electrically insulating type-B grounding was effective in suppressing low-frequency common-mode currents. Figures 4(a) and (b) show the measurement results for common-mode currents in the case where the shielding was grounded at both the ends and the grounding system was an IT system (Insulation-Terre system, Terre stands for earth in French). As can be seen, when shielded cables were used to suppress common-mode currents, it was necessary to combine them with an IT system. The gist of this report is as follows:

(1) When shielded cables are used in a TT system (Terre-Terre system), common-mode currents in low-frequency bands increase regardless of the grounding of their shielding, which leads to the frequent occurrence of electromagnetic interference.

(2) When the shielding is grounded only at the inverter-side end, the extent of suppression of common-mode currents in high-frequency bands changes depending on the impedance of the power supply and grounding systems.

(3) When the shielding is grounded at the induction-motor-side end, common-mode currents in high frequency bands increase in the entire grounding system.

(4) When the shielding is grounded at both the ends, it is possible to confine high-frequency common-mode currents within the shielded cables. However, low-frequency common-mode currents inevitably increase, as stated in (1) above.

(5) By arranging the grounding system in an IT system and grounding the shielding at both the ends, it is possible to suppress common-mode currents significantly.
Method for Evaluating Insertion Loss of EMI Filter Connected to Semiconductor Power Converters

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Keywords: conducted EMI noise, EMI filter design, insertion loss, common-mode equivalent circuit

In this paper, to design an EMI-filter effectively, a method for evaluating the insertion loss of the EMI filter connected to a semiconductor power converter is proposed.

High-frequency leakage current that may cause serious conducted EMI problems flows through an inverter system. Therefore, conducted EMI noise that flows from the inverter should conform to the regulations of an international commission, such as International Electrotechnical Commission (IEC). In order to conform to such regulations, EMI filters have to be connected to power converters. In general, the performance of an EMI filter is evaluated on the basis of the insertion loss of a 50Ω measurement system. However, the impedance of power converters is usually not set to 50Ω. As a result, the EMI filter design is often performed using a trial-and-error method because the noise reduction effect is different from the insertion loss.

Fig. 1 shows the proposed method for the measurement of the insertion loss of the EMI filter connected to the power converter. In this proposed method, the power converter, such as a half-bridge inverter, power drive system (PDS), is considered to be a capacitor for simplicity, because the leakage current flows via stray capacitors inside motors, cables, and IGBT modules. Then, the proposed measurement method is employed using the 50Ω measurement system and the capacitor.

In this study, the proposed method is validated by two experimental results: one is for the case of employing a half-bridge inverter and the other is the case of employing a PDS. Fig. 2 shows a system for measuring conducted EMI for the half-bridge inverter. The conducted EMI from the converter is measured in terms of the voltage V_{noise} across the resistance R_{LISN} in a line impedance stabilization network (LISN). Fig. 3 shows the measured results of the conducted EMI. The insertion loss connected to the inverter is derived by subtracting the measurement result for the case without the EMI filter from that for the case with the EMI filter.

Fig. 4 shows the measurement results of the insertion loss of an EMI filter. In Fig. 4, it is confirmed that the proposed measurement result disagrees with the conventional measurement result, especially below 1 MHz. In contrast, the comparison of Fig. 3 and Fig. 4 shows that the results of the proposed evaluation method connected to a power converter (Fig. 2) correspond with the experimental results below 4 MHz. Thus, the evaluation results show that the proposed method is equally suitable in both case, i.e., when a half-bridge inverter and when a PDS are used. Therefore, the proposed evaluation method helps to design an EMI filter because the derived noise reduction effect corresponds to the experimental one.
Reduction in Ripple Current and Self-inductance by Using Electromagnetic Coupling of Reactor

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Keywords: chopper, reactor, ripple current, duty factor, coupling coefficient

To produce DC current by using a multiphase reversible chopper, smoothing reactors are needed. When the smoothing reactors are employed, the chopper devise becomes large and heavy if electromagnetic interference is avoided.

The reduction in the ripple current by electromagnetic coupling contributes to making the chopper devise smaller and lighter. We deduced the relationships among the amplitude of ripple current, duty factor, electromagnetic coupling coefficient. To determine the loss and gain, we introduced the ratio of the amplitude of ripple current in each phase and in total combined of multiphase chopper system to that of the ripple current in one-phase chopper, $A_{ph}$, $A_{sum}$ respectively. This value indicates the reduction in not only the amplitude of ripple current but also self-inductance.

For a two-phase chopper, when duty factor is less than 0.5, the ratio is expressed as in Eqs. (1) and (2). In these equations, $\alpha$ is duty factor and $k$ is the electromagnetic coupling coefficient. (When duty factor becomes more than 0.5, $A_{ph}$, $A_{sum}$ are obtained by substituting $1 - \alpha$ for $\alpha$.) $A_{ph}$, $A_{sum}$ are shown in Fig. 1, Fig. 2 respectively.

$$A_{ph} = \frac{1}{(1 + k)(1 - \alpha)} \left( \frac{1}{1 - k} - \alpha \right)$$

$$A_{sum} = \frac{1}{1 + k} \left( \frac{1 - 2\alpha}{1 - \alpha} \right)$$

For $k_0 < k < 0$, both $A_{ph}$ and $A_{sum}$ become less than one. $k_0$ is the electromagnetic coupling coefficient corresponding to $A_{ph} = 1$ and $A_{sum} = 1$. $k_0$ is expressed as in Eq. (3).

$$k_0 = \frac{\alpha}{1 - \alpha}$$

To achieve considerable electromagnetic coupling efficiency, the following conditions have to be satisfied. The efficient area is shown in Fig. 3.

- The absolute value of $k$ should be less than $|k_0|$.
- Reactors should operate with differential coupling.

The minimum value of $A_{ph}$ analytically obtained is accurately determined. $k_{min}$ is defined as the electromagnetic coupling coefficient when $A_{ph}$ is the minimum value. $k_{min}$ is expressed as in Eq. (4), and $k_{min}$ values are shown by the broken line in Fig. 3.

$$k_{min} = 1 + \frac{\sqrt{1 - 2\alpha - 1}}{\alpha}$$

Finally, we applied an optimal electromagnetic coupling coefficient to the design of onboard reactors of electric railway vehicles. We estimate the effect of electromagnetic coupling. When $\alpha$ is 0.45 and $k$ is -0.52, $A_{ph}$ becomes 0.79 (from Eq. (1)). This result implies the following:

- When self-inductance is the same as that of one-phase chopper, thermal loss by ripple current is reduced to 62% in each phase.
- When the amplitude of ripple current is the same as that of one phase, the increase in weight of reactors is reduced to 58%.

Fig. 1. Amplitude of ripple current on each phase in the two-phase chopper system

Fig. 2. Amplitude of ripple current on total combined in the two-phase chopper system

Fig. 3. Area where ripple current is reduced (two phases)
Modeling of Multi-Degree-of-Freedom Motions for Motion Database

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Keywords: motion database, hidden Markov model, bilateral control, real-world haptics, motion control

Recently, the aging of workers and craftsmen are becoming a great issue because of low birthrate and longevity. The advanced skills of craftsmen is a precious property. Thus, importing knowledge of craftsmen to future generations is considered to be important. However, it is difficult to import such knowledge to many people at once. The “motion database” that realizes recording, searching, and reproduction of human motions is considered to be effective in overcoming this problem. By saving information about advanced techniques in the motion database, these techniques can be reproduced anytime, anywhere.

In order to construct the motion database, modeling of human motions is needed. By employing common modeling methods such as motion capture and by using an acceleration sensor, force information could not be obtained. However, when a motion is modeled, force information is important for the motion database, because the motion varies with the adjustment despite it’s trajectory remaining the same. In this paper, motion modeling by using force information and a searching method based on a hidden Markov model are proposed. Fig. 1 shows the overview of this paper. The motion is extracted by using a bilateral control system. The extracted motions are modeled and saved in the motion database, and then, the stored motions are searched by using the models. In this paper, the motion is evaluated on the basis of trajectory, angle of force, and amplitude of force.

![Fig. 1. Overview of the modeling and search methods proposed in this paper](image1)

In this paper, the motion is divided into straight-line phases. Fig. 2 shows the overview of inner phase of motion. \( \theta_A, \theta_B, \) and \( \theta_C \) are angles of the travelling direction of motion. The information related to motion consist of angle of velocity vector, amplitude of force vector, and angle of force vector. Further, the phases are divided into kinetic phase and static phase.

![Fig. 2. Overview of inner phase of motion](image2)

Next, the motion is searched by using a hidden Markov model. The feature vectors consist of angle of velocity vector, amplitude of force vector, and angle of force vector. By incorporating the information about force in feature vectors, it becomes possible to recognize motions that have same the trajectory but different force. Because the feature vectors of kinetic phase and static phase are different and because it is difficult to search all motion at once, an hierarchical-type searching method is used to search for an motion. Fig. 3 shows the overview of hierarchical-type searching. In the first hierarchy, motions are discerned as motions including static phase and other motions. In the second hierarchy, motions are discerned as each individual motion.

![Fig. 3. Hierarchical-type searching](image3)

In this study, to confirm the validity of the proposed motion modeling, nine types of motion are searched. Table 1 lists the recognition results. It shows that the motions were recognized with a high rate of accuracy by using the proposed method. Motions 5–9 are motions with the same trajectory but different force. Because the differences among motions 5–9 are only the forces of the different motions, conventional methods like motion capture could not recognize these motions. However, by using proposed method, these motions are recognized with high rate of accuracy. Availability of the model and the search method were confirmed by performing experiments.

![Table 1. Recognition results](image4)

When a motion is modeled, the motion is divided into straight-line phases. Fig. 2 shows the overview of inner phase of motion. \( \theta_A, \theta_B, \) and \( \theta_C \) are angles of the travelling direction of motion. The information related to motion consist of angle of velocity vector, amplitude of force vector, and angle of force vector. Further, the phases are divided into kinetic phase and static phase.

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Extended Summary

Workspace Based Controller Design and Performance Evaluation of MDOF Force Sensorless Bilateral System

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Keywords: bilateral system, workspace, operability, observer, multi-degree-of-freedom, force sensorless

Reducant multi-degree-of-freedom (MDOF) bilateral system in workspace is expected to be a key technology for the development of next generation robots because of the variety of feasible tasks. Nowadays, four channel bilateral structures based on acceleration control have been introduced to realize both position and force tracking in a bilateral system. Additionally, torque observers have been implemented to place force feedback without the use of torque/force sensors. However, differences in controller composition between the joint space and workspace are still unclear. In particular, in both spaces, observer designs are important for the realization of torque/force sensorless bilateral control. This paper presents a performance evaluation of an MDOF force sensorless bilateral system performed by considering the design space of observers by numerical and experimental analyses. The different types of bilateral controllers are shown in Table 1. Disturbance observer (DOB) compensates for the joint space disturbance. Workspace observer (WOB) compensates for the workspace space disturbance. Reaction torque observer (RTOB) is used to estimate the external torque in the joint space, while Reaction force observer (RFOB) is used to estimate the external force in the workspace. In order to compare six types of controllers, a simulation was carried out for touch motion. Figs. 1 and 2 show force responses. From these figures, it is confirmed that the manner of construct of the disturbance compensation loop and reaction force estimation loop is important. For accurate force estimation, the compensation loop of the disturbance observer should be designed to be identical to the reaction force observer loop or more outer loop than it.

Among the different types of constructible controllers, two types (DOB+RTOB and WOB+RFOB) were studied by conducting experiments. A circular trajectory with a radius of 60 mm was considered for 12 seconds. An evaluation function was used for the improvement of manipulability in null space. Figs. 3(a) and (b) show the attitude response of a DOB based controller and WOB based controller, respectively. Fig. 3(c) shows the manipulability value of both controllers. In Fig. 3(c), DOB+RTOB has higher manipulability than WOB+RFOB because DOB can compensate for the disturbance torque in the joint space and the control input in null space can operate as commanded. On the other hand, in the WOB based controller, the disturbance torque is compensated for by the null space, so control input in null space cannot operate according to commands. As can be seen in Table 2, there is a correlation between the manipulating-force impulse and manipulability. The higher the manipulability measure, the lower is the manipulating-force impulse. Consequently, it is important to maintain high manipulability measure when an operator considers the improvement of operability in a bilateral system.

Table 1. The pattern of observer based controllers

<table>
<thead>
<tr>
<th>Controller</th>
<th>DOB</th>
<th>WOB</th>
<th>DOB+WOB</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTOB</td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
</tr>
<tr>
<td>RFOB</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
</tr>
</tbody>
</table>

![Fig. 1. Simulation results (DOB based controller)](image1)

![Fig. 2. Simulation results (WOB based controller)](image2)

![Fig. 3. Experimental results](image3)

Table 2. Relationship between manipulating force and manipulability

<table>
<thead>
<tr>
<th>Controller</th>
<th>Manipulating-force(N·m)</th>
<th>Manipulability</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOB based controller</td>
<td>2.091</td>
<td>0.076</td>
</tr>
<tr>
<td>WOB based controller</td>
<td>5.308</td>
<td>0.067</td>
</tr>
</tbody>
</table>
Fast and Precise Positioning by Adaptive Feedforward Disturbance Compensation Using Interference Force Modeling

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Keywords: rotary table system, fast and precise positioning, interference suppression, adaptive control

This paper presents a model-based feedforward compensation approach that can be used for the fast and precise positioning of a rotary table system with two drive actuators. Since the rotary table system is composed of two axes to position the load displacement and/or pose, nonlinear friction at the ball guide between the gear and the table behaves as an interference force, which deteriorates the positioning performance of the primary axis (R-axis) and the slave axis (Q-axis). Therefore, in this research, the interference force between two axes are compensated by a disturbance-model-based feedforward approach. In the approach, a mathematical disturbance model formulated and parameterized by using an iterative learning process can estimate the actual disturbance including the interference, and the model can be adapted by a least-squares method to provide adaptive properties against disturbance variations. The proposed positioning control involving disturbance modeling and compensation has been verified by performing experiments with a prototype.

Fig. 1 shows a block diagram of the proposed two-degrees-of-freedom positioning system with disturbance compensation and adaptive system, where \( \tau_{dis} \) is the disturbance with interference force, Adaptive System is a least-squares-method operation block using a disturbance observer, \( \hat{\tau}_d \) is the disturbance model output, \( N \) and \( D \) are feedforward compensators, \( C \) is a feedback compensator and subscripts r and q represent the R and Q axes. This system updates the disturbance model parameters \( \hat{K}_r \) and \( \hat{K}_q \) to minimize the error between \( \hat{\tau}_d \) and \( \tau_{dis} \).

Fig. 2 shows positioning waveforms with and without disturbance compensation under with and without model adaptation. In the figure, the dotted lines correspond to experimental waveforms without disturbance compensation before warming-up, while the solid lines and the dashed-dotted lines correspond to experimental waveforms with disturbance compensation before and after warming-up under without model adaptation. The broken lines, on the other hand, correspond to waveforms with adaptive disturbance compensation after warming-up. The upper waveforms in Fig. 2 indicate the R-axis response, while the lower waveforms indicate the Q-axis response. Regardless of the temperature fluctuation, the waveforms show that the proposed disturbance compensation can successfully prevent undershoot in the position errors of R and Q axes, facilitating the realization of the required positioning performance.