A Novel Method on Disturbance Analysis and Feed-forward Compensation in Permanent Magnet Linear Motor System

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***Abstract*—Linear motor system has been developed to achieve high speed and high precision motion control in linear motion system, since rotary type motor has backlash and hysteresis due to mechanical parts like chain, belt or screw. However, paradoxically, linear motor system becomes more sensitive to the external disturbance, because it doesn't have such transmission mechanism. Many studies have been focused on detent force which have dominant and position dependant non-linear properties among the external disturbances. But the solutions suggested by them are mostly complicated and difficult to apply due to the non-linear property of detent force. In this paper, a novel method to analyze the disturbance magnitude related to the harmonics order is introduced. It is based on a disturbance observer that is famous for its simple but robust and powerful scheme to eliminate disturbance. Nevertheless, from the implementation perspective, there exists a limitation with direct feedback of the disturbance observer output. It is because the bandwidth of disturbance observer is limited by measurement noise, while the disturbance gets higher frequency with the speed due to the position dependant property of detent force. To resolve this problem, feed-forward controller with a function of position is suggested. Through experimental results, the suggested method was verified to have much better performance compared to direct feedback of disturbance observer.**

***Keywords*-disturbance observer; disturbance identification; lumped disturbance compensation; permanent magnet linear motor.**

I. Introduction

Demand on operating safety and precision motion control in servo system has been increased. And the great development in electrical device is achieved, while the cost and size of them are both reduced significantly due to mass fabrication and MEMS technology. These phenomena have led to the growth of motor application as actuator for decades. However, in the case of linear motion system with rotary motors, it needs transmission mechanisms such like belt, chain and screw for changing from rotary motion to linear motion. These mechanisms inevitably lead to problems of backlash, hysteresis, bad energy efficiency and so on. Consequently, the linear motor in which the indirect mechanism is eliminated is developed. But paradoxically, due to the absence of indirect mechanisms, the linear motor system becomes more sensitive to model uncertainties and external disturbances. By this reason, many researches[1][2][3] have been performed to achieve high precision motion control on linear motor system.

In general, disturbances in motor system are divided into position dependant detent force and velocity dependant friction force. The friction force can be considered as a simple constant except low speed region where the Stribeck effect[4] is quiet considerable. On the other hand, detent force appears in position dependant sinusoidal form, since it is made by mutual attraction between magnets and iron-core in iron-core type permanent magnet motor. Due to this position dependant characteristic, detent force has higher frequency components at higher speed, while the Stribeck effect in friction force becomes negligible at higher speed. With this reason, wide studies on detent force[5][6][7] have been conducted. However, in the implementation point of view, applying the solution on detent force and friction force separately, is inconvenient and complex. For that reason, disturbance observer technique, which is one of the most simplest but powerful method among many of disturbance estimation and compensation schemes, is adopted in this research.

The output of disturbance observer is assumed to be a lumped disturbance. It is utilized for the lumped disturbance compensation via a novel off-line analysis. In the realization of compensator design, feed-forward method is adopted rather than direct feedback of the output of disturbance observer. This is due to the limitation of disturbance observer especially on higher traveling speed. Q-filter a kind of low pass filter is attached to the end of disturbance observer for the sake of measurement noise rejection. Therefore, there exists the limit on bandwidth of disturbance observer. As mentioned above, detent force is position dependant. This property makes the frequency of detent force larger at higher traveling speed while the bandwidth of disturbance observer is limited. On the other hand, there is no such limitation in the feed-forward method. This is why feed-forward method is adopted in this research for the disturbance compensation, and its effectiveness is verified by experimental results.

The rest of this paper is organized as follows. Section II describes the linear motor plant model and mathematical

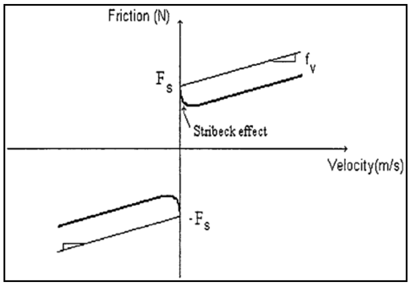

Figure 1. General friction model.

analysis on detent force. Section III illustrates the novel method on disturbance identification using disturbance observer. And the disturbance compensation by feed-forward is presented in Section IV. Section V shows experimental results to demonstrate the effectiveness of suggested feed-forward method compared to direct feedback scheme of disturbance observer output. Finally, conclusions are given in section VI.

II. Mathematical analysis on detent force

The mechanical dynamics of motor system is given by

$$M\ddot{x}(t)+B\dot{x}(t)=u(t)-d(t) \tag{1}$$

where M is the mass of the mover, B the viscous friction coefficient, $x(t)$ the position of the mover, $u(t)$ the thrust force, $d(t)$ the lumped disturbance including the detent force and the friction force.

And a general friction force model is given as follows:

$$F_{fric}(\dot{x})=[f_c+(f_s-f_c)e^{-|\dot{x}/\dot{x}_s|^2}+f_v\dot{x}]sgn(\dot{x}) \tag{2}$$

where f_c is the minimum level of Coulomb friction, f_s the level of static friction, $\dot{x}_s$ the lubricant parameter determined by empirical experiments to describe the Stribeck effect, f_v the viscous friction parameter, sgn the sign function.

Fig. 1 shows this friction model. By extracting the viscous friction term f_v in (2) to outwards as B in (1), it is able to consider only Coulomb friction as friction force except low traveling speed range where the Stribeck effect is not negligible.

Due to the structural characteristic of iron-core type permanent magnet motor, the detent force is represented as follows:

$$F_{det}(x)=\sum_{k=1}^{N}A_k sin(\frac{2\pi}{x_p}kx+x_{0k}) \tag{3}$$

where k is the number of harmonics, x_p the pole pitch, x_0 the phase shift.

The electrical dynamics of motor system is given by

$$\begin{aligned} v_i &= Ri_i+L_s\frac{di_i}{dt}+\dot{x}k_i \\ k_i(\theta) &= K_{ei}sin(\theta-(i-1)\frac{2\pi}{3}) \\ i_i(\theta) &= I_i sin(\theta-(i-1)\frac{2\pi}{3}) \\ \theta &= \frac{\pi}{\tau}x \end{aligned} \tag{4}$$

where v_i is the applied voltage, R the phase resistance, i_i the phase current, L_s the synchronous inductance, k_i the shape function of back EMF, subscript the phase number, K_e the amplitude of sinusoidal EMF shape function, τ the extension of a single magnetic pole, I the amplitude of sinusoidal current.

The thrust force in ideal case (i.e., K_{e1}=K_{e2}=K_{e3} and I_1=I_2=I_3) is given by

$$u=f_m=\frac{3}{2}K_eI \tag{5}$$

However, in the existence of difference in current amplitude among three phases (e.g., I_2=$I_1+\Delta_2$, $I_3=I_1+\Delta_3$), the 2nd order harmonics are created in the thrust force as follows:

$$\begin{aligned} f_m = &\frac{K_e}{2}(3I+\Delta_2+\Delta_3) \\ &-\frac{K_e}{2}[\Delta_2cos(2\theta-\frac{4\pi}{3})+\Delta_3cos(2\theta+\frac{4\pi}{3})] \end{aligned} \tag{6}$$

with the current offset of δ_2 and δ_3, the thrust force is added by the 1st order harmonics as follows :

$$f_m=\frac{3}{2}K_eI+K_e\delta_2sin(\theta-\frac{2\pi}{3})+K_e\delta_3sin(\theta+\frac{2\pi}{3}) \tag{7}$$

and in the case of over or under phase shifted than 120 degree in current(e.g., α_2 and α_3), the 2nd order harmonics are generated as follows:

$$\begin{aligned} f_m = &\frac{K_eI}{2}(cos\alpha_2+cos\alpha_3+1) \\ &-\frac{K_eI}{2}(cos\alpha_2-cos\alpha_3)cos(2\theta-\frac{4\pi}{3}) \\ &+\frac{K_eI}{2}sin\alpha_2sin(2\theta-\frac{4\pi}{3}) \\ &-\frac{K_eI}{2}(1-cos\alpha_3)cos(2\theta) \\ &+\frac{K_eI}{2}sin\alpha_3sin(2\theta+\frac{4\pi}{3}) \end{aligned} \tag{8}$$

but this analysis is based on the assumption that the current waveform has a perfect sinusoidal shape. In real case with imperfect waveforms, more than the 2nd order harmonics, e.g., the 4th order, the 6th order, and the 12th order harmonics are reported as significant detent force[8][9]. And dominant harmonics order and magnitude of detent force are the original property of each motor system. The illustration to identify the original property of this motor system is presented in following section.

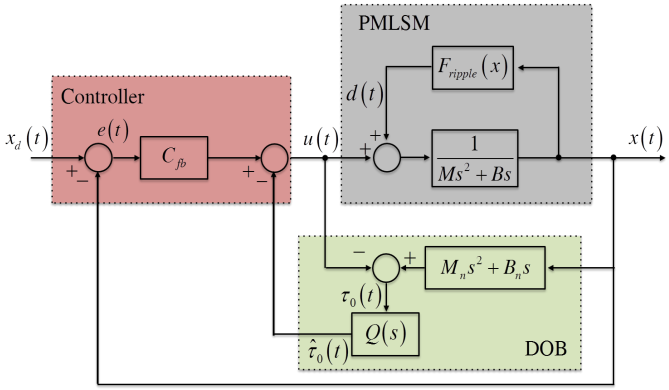

Figure 2. Structure of disturbance observer.

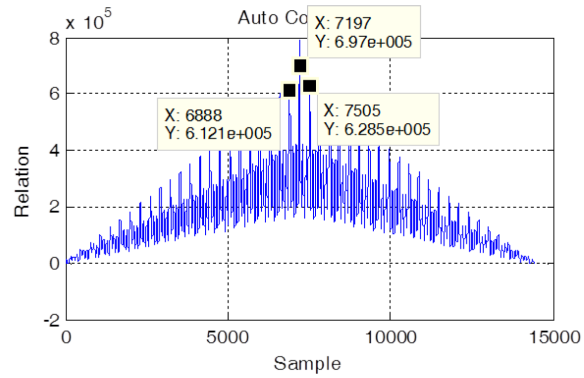

Figure 4. Result of after auto-correlation.

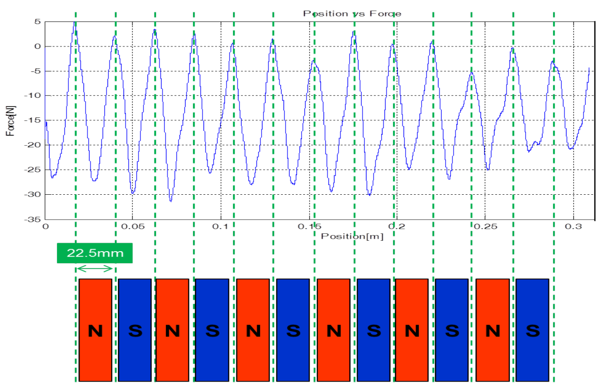

Figure 3. Output of disturbance observer.

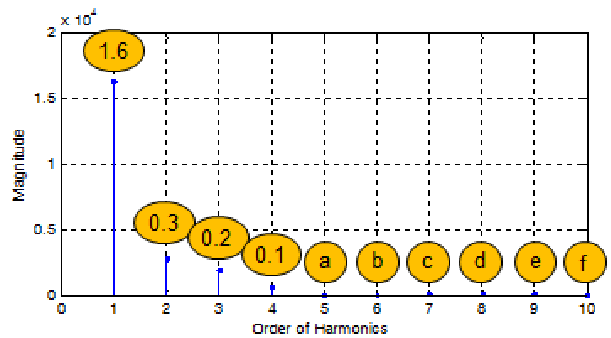

Figure 5. Result of fast fourier transform

III. Disturbance Identification using Disturbance Observer

The disturbance observer is a quiet simple but powerful and robust technique. There is no need to definitize whether detent force or friction force, and it compensates the disturbance in lumped form.

Fig. 2 shows the structure of disturbance observer. The Q-filter attached to the end of disturbance observer is a kind of low pass filter to reject the measurement noise. The output of the Q-filter of disturbance observer is recognized as real lumped external disturbance. An example of that output is shown in Fig. 3. Using these results of repeated experiment at various conditions, the lumped disturbance is estimated as following steps.

First, the exact sample number for a sinusoidal period in Fig. 3 is found by using the auto-correlation method. This method utilizes the convolution function in MATLAB. As an example, the output of auto-correlation is shown in Fig. 4. By calculating the number of samples between peak to peak, the actual sample number for a period is obtained. Second, the full data in Fig. 3 is cut into each period using the information attained in the previous step. And with the fast fourier transform technique, the magnitude of each harmonics order of external disturbance related to each period is calculated as shown in Fig. 5. Higher frequency components than the 10^{th} order harmonics are considered as measurement noise and rejected by Q-filter. Therefore, components from the 1^{st} to the 10^{th} order harmonics are assumed to be entire external disturbance. The cumulated ratio of magnitude up to each harmonics order to entire (i.e., to the 10^{th} order harmonics) is figured out in Fig. 6. With the result of repeated operation of these step shown in Fig. 7, following conclusion is drawn.

1) Analysis on external disturbance eliminating capability: The disturbance in this permanent magnet linear motor system is supposed to be eliminated more than 75% by accurate compensation of up to the 2^{nd} order harmonics, more than 87% by up to the 4^{th} order harmonics and more than 93% by up to the 6^{th} order harmonics. The improved amount by compensation from up to the 4^{th} order harmonics to up to the 6^{th} order harmonics is not so significant compared to that of the 2^{nd} to the 4^{th} order harmonics.

Consequently, for the sake of simplicity and the advantage on computation, the compensation scheme up to the 4th order harmonics is adopted in this paper. Fig. 8 shows the disturbance identification ability with the harmonics order. In Fig. 8, left-top shows the force ripple that has the

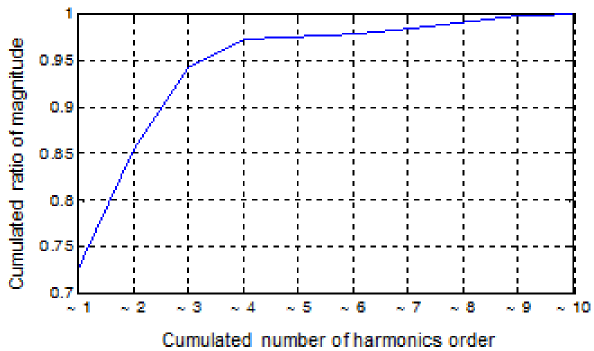

Figure 6. Cumulated curve of disturbance magnitude.

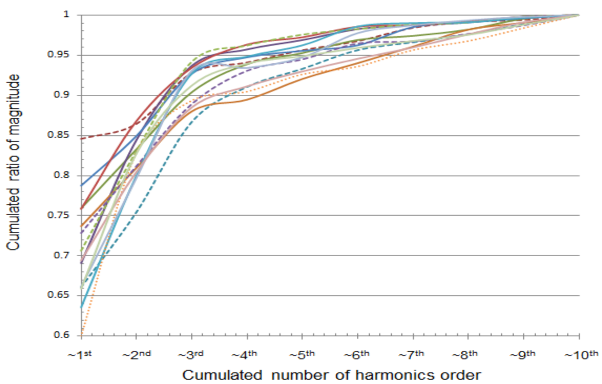

Figure 7. Repeated cumulated curve of disturbance magnitude.

components up to the 1^{st} order harmonics, right-top up to the 2^{nd} order harmonics, left-bottom up to the 3^{rd} order harmonics, right-bottom up to the 4^{th} order harmonics.

IV. Disturbance compensation by feed-forward

In the previous section, disturbance observer was utilized to identify the lumped disturbance. However, there exists a limitation on disturbance observer to compensate the external disturbance by direct feedback of the output of disturbance observer.

As mentioned above, dominant and non-linear disturbance of detent force has a property of position dependant. This property makes the disturbance of identical harmonics order have higher frequency at higher traveling speed condition. On the other hand, the bandwidth of Q-filter for measurement noise reduction is limited. Furthermore, the low pass filter property of Q-filter induces time-delay in the disturbance observer output. With these reasons, the performance on disturbance compensation by direct feedback of the output of disturbance observer gets worse with motor speed. For a better understanding of this, Fig. 9 is prepared. As shown in the figure, Q-filter bandwidth is limited to $50Hz$. In Fig. 9 the case of (a), that has relatively low travel speed of $0.15m/s$, almost components up to the 8th order harmonics

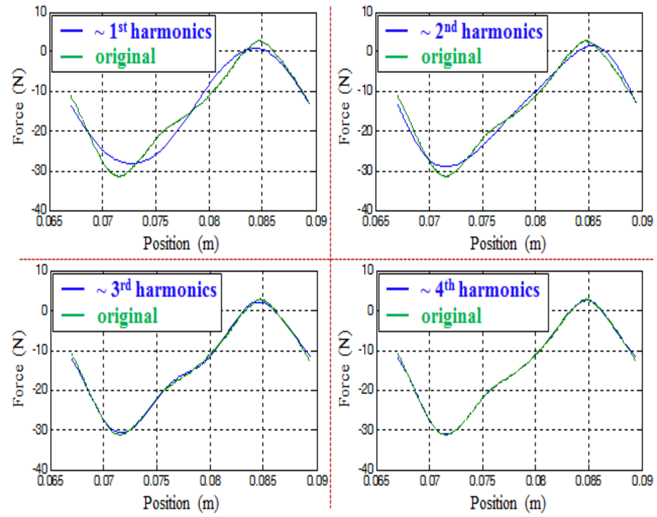

Figure 8. Disturbance identification ability comparison.

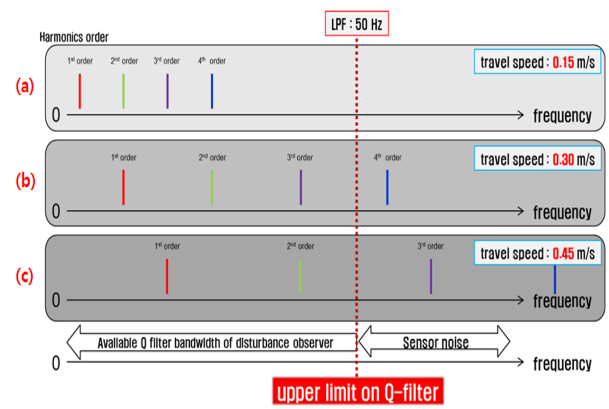

Figure 9. Limitation of disturbance observer.

are supposed to be compensated. In this case, it might be enough with disturbance observer. But with the increasing of travel speed up to about $0.30m/s$, which is the case of (b), the disturbance compensating performance of disturbance observer shows a significant drop. Further increasing in the motor speed up to about $0.45m/s$, which is the case of (c), just only the components of 1^{st} order and 2^{nd} order harmonics are able to eliminated by disturbance observer. The emphasis here is that traveling speed of $0.5m/s$ is by no means not extremely high from the point of industrial application.

Therefore, the authors extracted the lumped disturbance as a function of position from the disturbance observer output by off-line analysis. And by compensating this disturbance with a feed-forward function of position, the weakness on higher speed condition of direct feedback method described above get resolved.

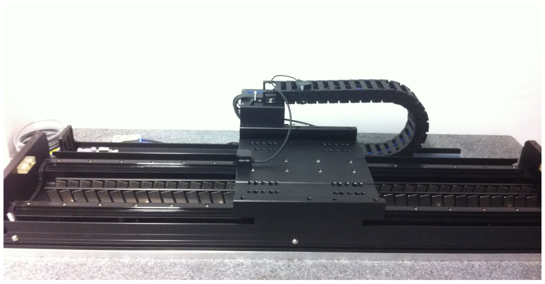

Figure 10. Experimental prototype PMLSM motion system.

Table I
PARAMETERS OF THE PMLSM MOTION SYSTEM

Parameter	Symbol	Value	Unit
Mover mass	M	8.70	kg
Viscous friction coefficient	B	80.70	N/m/s
Pole pitch	x_p	22.5	mm

V. EXPERIMENTAL RESULTS

To show the effectiveness of the disturbance compensation technique described in the previous section, experiments are implemented on the permanent magnet linear synchronous motor system.

A. Experimental setup

All experiments were carried out based on the prototype permanent magnet linear synchronous motor(PMLSM) motion system depicted in Fig. 10. The system parameters are given in Table I. These parameters were obtained by a system identification method since it is a prototype motor. The PWM inverter used for the experiments has $10kHz$ switching frequency and is controlled by a dSPACE DS1103 board. The current and position controllers were executed at $50\mu sec$ and $0.5msec$ loop time, respectively. An optical linear encoder, which has a resolution of $0.5\mu m$, was utilized to measure the position of PMLSM.

B. Verification of suggested method

As described in Fig. 9, the original bandwidth of Q-filter is $50Hz$. For the condition that the 4^{th} order harmonics of disturbance is beyond that limit, motor traveling speed should be about $0.30m/s$. However, due to the overall distance of $50cm$ of PMLSM, the experiments were conducted by reducing the Q-filter bandwidth instead of increasing the motor speed.

1) Comparison in case (b) of Fig. 9: For the imitation of case (b) in Fig. 9, experiments were conducted with traveling speed of 0.12m/s and Q-filter bandwidth of 17Hz. To improve the reliability on the experimental results, each condition was conducted three times. The results are shown in Fig. 11 and Fig. 12. By comparison of upper sub-figures of them, there is almost no difference in control inputs. However, in the lower sub-figures, the RMS error

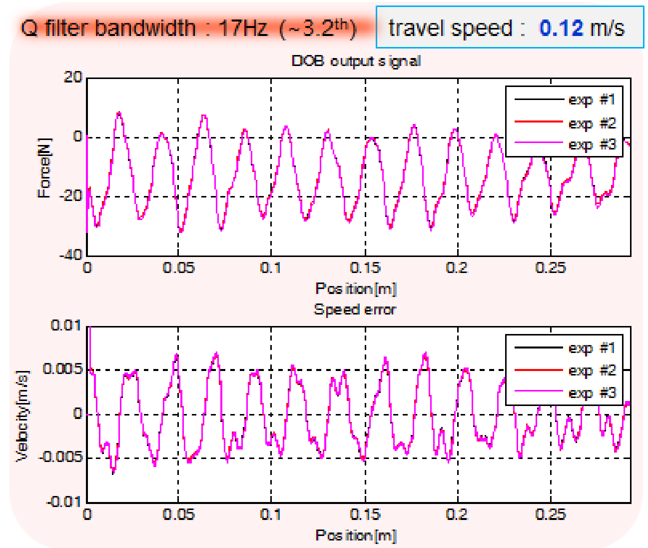

Figure 11. Disturbance compensation result using feedback of disturbance observer output (up to the 3^{rd} order).

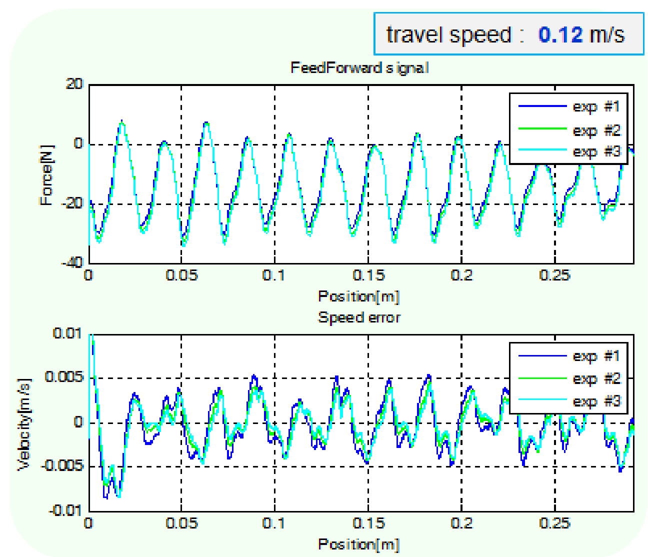

Figure 12. Disturbance compensation result using feed-forward (up to the 4^{th} order).

by suggested feed-forward method is $0.0023m/s$, compared to that by disturbance observer of $0.0036m/s$. Namely, the RMS error is reduced by 36%.

2) Comparison in case (c) of Fig. 9: For the verification in case (c) in Fig. 9, experiments were conducted with traveling speed of 0.14m/s and Q-filter bandwidth of 13Hz. The results are shown in Fig. 13 and Fig. 14. Similarly to the previous case, there is no outstanding difference between two control inputs. Nevertheless, RMS error reduction of 50% is acquired by suggested feed-forward method.

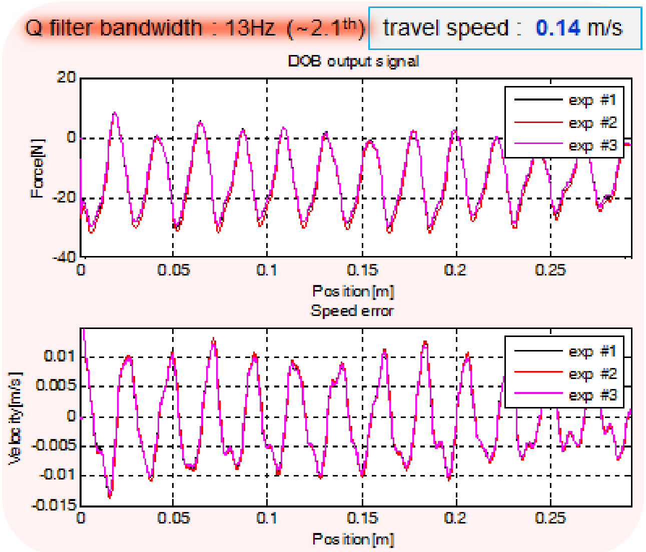

Figure 13. Disturbance compensation result using feedback of disturbance observer output (up to the 2^{nd} order).

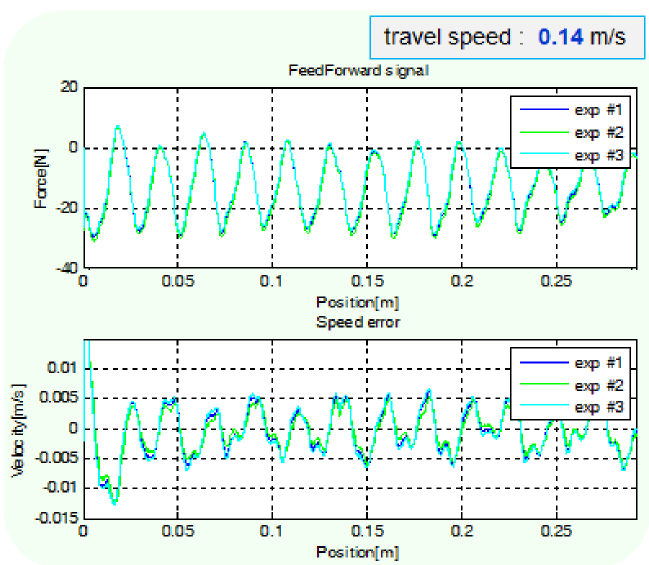

Figure 14. Disturbance compensation result using feed-forward (up to the 4^{th} order).

VI. Conclusion

In this study, the disturbance in permanent magnet linear motor system is investigated. First, with the disturbance observer, which is famous for its simplicity, powerfulness and robustness, it was able to identify the magnitude of disturbance related to its harmonics order. And a novel method on disturbance analysis by off-line has been presented. This could be a technical help and ground for how determine the harmonics order for disturbance compensation to achieve target performance. Furthermore, on-line disturbance compensation method by feed-forward control, which has the basis on disturbance observer output is suggested. It is shown by experimental results that this method can overcome the limitation of direct feedback control of disturbance observer especially at high traveling speed.

On the other hand, since the suggested method utilizes a function of position for feed-forward control, initial position estimation algorithm is necessary for a better performance. And this is now on-going study by the authors.

Acknowledgment

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