

Article

Improved Adaptive Feedforward Controller Based on Internal Model Principle with Disturbance Observer for Laser-Beam Steering Systems

Jung-Gon Kim 

Ground Technology Research Institute, Agency for Defense Development, Daejeon 34186, Republic of Korea; jgkim78@add.re.kr

Abstract: This study presents an effective control algorithm to improve the robustness of fast steering mirror (FSM)-based laser-beam steering systems against dynamic disturbances, such as repetitive disturbances resulting from operating conditions. A stable control system must be able to maintain the required high-precision control, even when dynamic disturbances affect the FSM system. In this study, an improved control method is proposed using an internal model principle (IMP)-based nonlinear controller with a disturbance observer (DOB) for the FSM system. This IMP-based controller with DOB can attenuate the residual control-error signal under dynamic disturbance conditions.

Keywords: laser-beam steering; fast steering mirror; adaptive feedforward control; tip-tilt control system; internal model principle; disturbance observer



Citation: Kim, J.-G. Improved Adaptive Feedforward Controller Based on Internal Model Principle with Disturbance Observer for Laser-Beam Steering Systems. *Appl. Sci.* **2024**, *14*, 5631. <https://doi.org/10.3390/app14135631>

Academic Editor: Zhi-Ting Ye

Received: 9 April 2024

Revised: 27 May 2024

Accepted: 25 June 2024

Published: 27 June 2024



Copyright: © 2024 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Fast steering mirror (FSM)-based laser-beam steering (LBS) systems are used in various optical tracking control systems, such as long-range laser communication, line-of-sight (LOS) stabilization, and adaptive optics [1–5]. In addition, these systems are increasingly mounted on moving platforms, such as spacecraft, satellites, airplanes, ships, and vehicles [6–8]. However, the LBS control system must maintain the aiming point in the target plane while minimizing factors that cause jitter in the presence of disturbances. In applications, jitter usually is caused by the vibration of the optical bench through which the laser beam travels [9].

The robustness design of FSM systems is typically approached as two separate cases. First, the design of structural parameters must be considered to satisfy the control requirements of the target platform. FSM systems require the flexible hinges as rigid elastic supports to meet structural stiffness and drive forces for a certain range of strokes. Flexible hinges have a simplified structure, integrated design, and machining to guarantee the transmission resolution and accuracy, as well as good rotational response, because they eliminate mechanical friction and non-linearity [10,11]. In addition, the flexible hinges can be attenuated to the mechanical vibration, which leads to reduced rotational position error and increased precision performance [12]. A flexible hinge should approximate a mechanical structure with higher axial/torsional stiffness and lower rotational stiffness to ensure the desired flexible segment movement.

Second, with high-precision control performance, it is necessary to design a control system with fast response characteristics and disturbance rejection control performance [13–15]. FSM systems typically use voice coil actuators or PZT actuators, with VCA having a longer stroke, while their response, output force, and resolution are primarily suitable for most applications. PZT actuators are also suitable for applications that require higher resolution and faster settling times than VCA. High-precision tip-tilt controllers for FSM systems are designed to ensure that the aforementioned VCA or PZT actuator maintains an extremely small rotational position in the presence of dynamic disturbances to satisfy the desired

operating conditions. Therefore, several studies have been conducted to achieve high-precision control performance. A method to eliminate the vibration effect of PZT actuators has been proposed [16]. A notch filter was developed as an effective method to eliminate the main resonant mode of FSM systems [17,18]. Furthermore, an input shape controller and an integral resonance controller were developed [19,20].

In general, several methods can be adopted to improve the performance of the dynamic disturbance attenuation for high-precision motion control systems. Particularly, the iterative controllers and adaptive feedforward cancellation (AFC) schemes have been applied to cancel out the repeatable disturbances resulting from the operational condition of the target application [21,22]. Iterative control algorithms are the most widely used for disturbance rejection, as either internal or external model-based controllers [23]. Discrete-time iterative controllers based on the internal model principle (IMP) have been analyzed [24]. As a disturbance-attenuation control system, an IMP-based control algorithm is commonly used in which a model of the disturbance-generating system is included in the feedback system. However, owing to the hardware limitations of the servo loop in our FSM control system, classical AFC schemes cannot be used to precisely control the rotational position. In order to avoid the above-mentioned problems, a basic idea to suppress disturbances emerges, which estimates the influences of external disturbances independently by using the disturbances observer and then eliminates the perturbation through the feedforward method. This feedforward method was named the disturbance observer (DOB) method [25–27].

It has been applied to several mobile devices with high-precision control systems, such as robot motion control, the swing arm actuator in the hard disk drive, the VCA in the optical disk drive, and the permanent magnet synchronous motor control [28–33]. To improve the control performance of the original control system for the FSM system, high open-loop gain in the dynamic disturbance frequency domain is needed to sufficiently attenuate disturbances. FSM systems commonly use proportional–integral (PI) controllers with high bandwidth owing to their robustness to modeling errors and simplicity of implementation [34,35]. In addition, the addition of a disturbance observer (DOB) to the base controller significantly improves the disturbance-attenuation performance because of its simplicity and suitability for real-time implementation [36,37]. Consequently, DOB implementation typically imposes a very light computational burden, and it is inexpensive because additional sensors are not required. Recently, several studies have developed robust FSM control systems by using DOB-based controllers to improve tip-tilt control performance.

In this study, we propose a more reliable tip-tilt control algorithm by using an IMP-based controller with DOB for the FSM system to reduce the control-error signal (CES) in the presence of dynamic disturbances. In experiments involving an analysis of periodic disturbances under operating conditions, we report the use of IMP-based control with a DOB to attenuate disturbances of a few frequencies. The remainder of this paper is organized as follows. Section 2 introduces the basic FSM control system. In Section 3, an IMP-based controller with a DOB is described, and its performance is analyzed. Section 4 describes the experiments conducted to verify the proposed method. Finally, our concluding remarks are presented in Section 5.

2. FSM Control System

2.1. Dynamic Characteristics of Piezoelectric (PZT) Actuator

In this study, the high-precision FSM system consists of a PZT actuator as the mechanical part, an actuator amplifier, and a sensing signal processing unit as the electrical part. In addition, the mirror-mounted piezoelectric (PZT) actuator is used to drive the FSM system to achieve the tip-tilt motion. In general, it is necessary to identify the frequency response performance of the real plant in order to design the control system. Here, the frequency response of the real plant (i.e., FSM system) was analyzed using a dynamic signal analyzer (35670A). The identified dynamic characteristics of the real plant are summarized

in Table 1. In addition, from the measurement of identification specifications for the plant, the frequency response of the real plant and modeled plant are illustrated in Figure 1.

Table 1. Identified dynamic characteristics of real plant.

Specification	Value
Resonance frequency	397.1 Hz
5 Hz sensitivity	166.7 $\mu\text{rad/V}$
Gain of voltage amplifier	10 V/V
Gain of sensor amplifier	0.006 V/ μrad

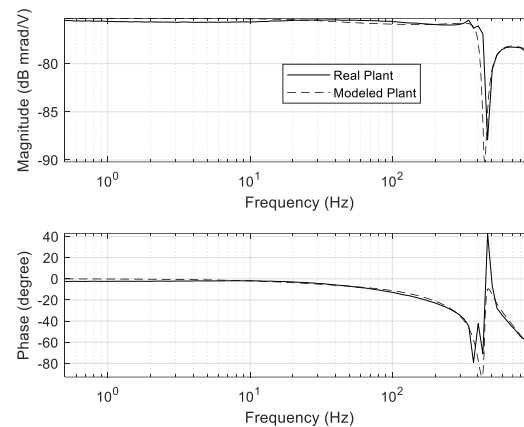


Figure 1. Frequency response of real plant and modeled plant.

Moreover, the nominal plant is modeled on a second-order transfer function and can be expressed as follows:

$$P_n(s) = \frac{3,891,000}{s^2 + 1651s + 4,911,000} \quad (1)$$

The configuration of the FSM platform for high-precision tip-tilt motion control is shown in Figure 2. It consists of a real plant and a real-time control platform used to realize the tip-tilt motion system. A Scalexio autobox (dSPACE) is used as the real-time control platform. In addition, a mirror-mounted PZT actuator (S-340) and an amplifier module (PI Ceramic GmbH, Lederhose, Germany) are used in the tip-tilt motion system.



Figure 2. Configuration of fast steering mirror (FSM) platform: (a) Scalexio AutoBox (dSPACE) and (b) tip-tilt actuating platform (PI Ceramic GmbH).

2.2. Tip-Tilt Controller of FSM Control System

Proportional–integral (PI) controllers are widely used in real control systems as the tip-tilt controllers of FSM control systems. Moreover, tip-tilt controllers are designed to achieve the designed gain margin, phase margin, crossover frequency, and loop gain. The

transfer functions for continuous time and discrete time for the PI controller are denoted by $C(s)$ and $C(z)$, respectively, and expressed as follows:

$$C(s) = k_p + \frac{k_i}{s}, \quad (2)$$

$$C(z) = k_p + \frac{k_i T_s Z}{z - 1}, \quad (3)$$

Here, k_p and k_i refer to proportional gain and integral gain, respectively, and the control gain should be chosen based on a balance of stability and performance. In this paper, the tunable parameters (k_p and k_i) of the PI controller are manually designed in the experiment and set to be $k_p = 0.75$ and $k_i = 950$. Figure 3 depicts the open-loop transfer function of the PI controller designed for the FSM control system in this study. The margins of gain and phase are 6.03 dB and 47.1° , respectively. Also, the crossover frequency and loop gain are 111 Hz and over 40 dB, respectively. Moreover, the disturbance-attenuation performance of the designed PI controller for the FSM control system is illustrated in Figure 4.

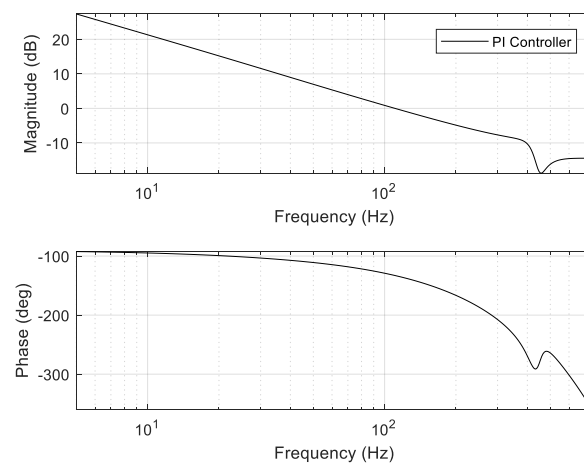


Figure 3. Open-loop transfer function of the proportional–integral (PI) controller in FSM control system.

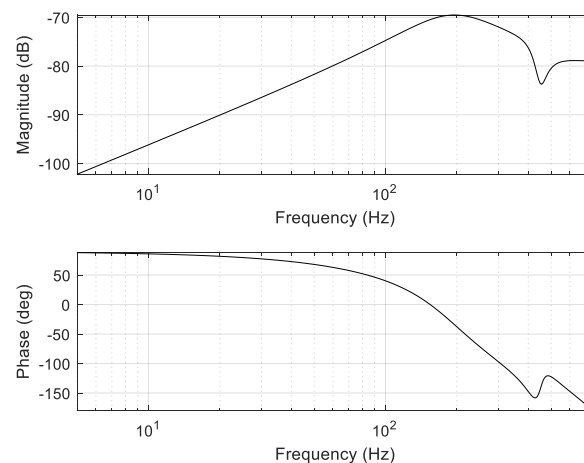


Figure 4. Disturbance–attenuation performance of FSM control system.

3. Disturbance-Rejection Control Algorithm for FSM System

3.1. IMP-Based Controller

To enhance the tip-tilt control performance when dynamic disturbances are applied to the target application, a control system can be designed in which an IMP-based controller is attached to the feedback loop of the base control. Furthermore, the IMP-based control algorithm is available for the rejection of sinusoidal disturbances, and they can be simply

extended to the case when multiple sinusoidal components are present. As illustrated in Figure 5, a feedback controller with IMP can be canceled out faster and more accurately than in an unmodified tip-tilt controller. In addition, the proposed IMP-based controller modifies the AFC algorithm more easily, considering the frequencies of various disturbances. However, when the rotational position exceeds the predefined threshold in the presence of nonperiodic disturbances, such as external shock, the feedback loop through the IMP-based controller is opened, as depicted in Figure 5, because the control performance of the system for nonperiodic disturbances may degrade. Therefore, IMP-based controllers are typically used in control systems as nonlinear controllers.

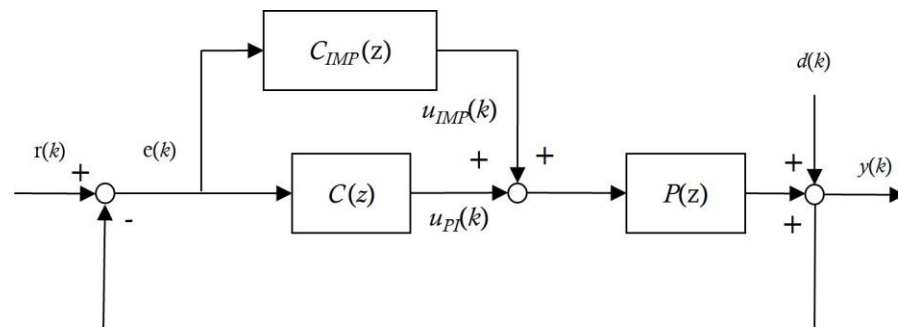


Figure 5. Schematic-diagram of FSM control system with IMP.

The transfer function of the IMP-based controller is denoted C_{IMP} . The continuous-time type and discrete-time type are denoted by $C_{IMP}(s)$ and $C_{IMP}(z)$, respectively, and can be obtained as follows:

$$C_{IMP}(s) = g \frac{\cos(\varnothing)s - \sin(\varnothing)\omega}{s^2 + \omega^2}, \quad (4)$$

$$C_{IMP}(z) = g \frac{\cos(\varnothing)z - \cos(\omega T_s + \varnothing)z}{z^2 - \cos(\omega T_s)z + 1}, \quad (5)$$

where sampling time, periodic frequency, adaptive gain, and control gains of the IMP-based controller are denoted as T_s , ω , g , and ϕ , respectively. This presented that the IMP-based controller is input/output equivalent to a linear time-invariant controller, even though the whole adaptive structure is described by linear time-varying differential equations. It is important to note that this transfer function has a zero at $s = -\omega \tan(\phi)$.

For the cancellation of periodic disturbances, the control input of an IMP-based controller has the following form in discrete time:

$$u(k) = \hat{a}(k)\cos(\omega T_s k) + \hat{b}(k)\sin(\omega T_s k), \quad (6)$$

The discrete-time update laws for the elimination of the disturbance are as follows:

$$\hat{a}(k) = \hat{a}(k-1) + g e(k) \cos(\omega T_s + \varnothing), \quad (7)$$

$$\hat{b}(k) = \hat{b}(k-1) + g e(k) \sin(\omega T_s + \varnothing), \quad (8)$$

where update laws parameter $e(k)$ is the control error, and g is the adaption gain of the IMP-based controller. The adaption gain g can be selected experimentally. If it is large, the magnitude of the open-loop transfer function at the disturbance frequency is larger, and the magnitude of the disturbance reduction performance is smaller. Moreover, the control performance of the system can be extremely unstable in other frequency regions because the sensitivity transfer function of the control system in those regions may attenuate in accordance with the Bode integral theorem. Therefore, the fundamental design of the IMP-based controller must be such that the control algorithm can be attenuated reliably. The disturbances whose frequencies correspond to those at which the control gain of the

IMP are infinite. In addition, the IMP-based control gain ϕ at ω (periodic frequency) is obtained as follows:

$$\phi = \angle \frac{P(z)}{1 + P(z)C(z)}, \quad (9)$$

where $P(z)$ is the designed FSM control system, and $C(z)$ is the PI controller.

As illustrated in Figure 6, according to the results of the experiment conducted to analyze uncompensated CES, periodic disturbances of several frequencies in the CES are generated primarily by the operating conditions. In particular, in the analyzed residual CES, periodic disturbance characteristics are generated during tip-tilt control owing to the vibration of the platform cooling fan. The power spectrum of the uncompensated CES shows that the disturbance occurs at integer multiples of the fundamental rotating frequency (i.e., 60 Hz) of the cooling fan. In addition, two specific peaks are formed at 65 and 71 Hz, and they are not harmonic frequency components of the fundamental rotating frequency of the cooling fan. These disturbance frequencies may be attributed to the mechanical resonances of the platform. Therefore, to eliminate periodic disturbances, such as the harmonic component resulting from rotation conditions of the cooling fan and mechanical resonance frequencies of the platform, the FSM control system is designed using an IMP-based controller, as illustrated in Figures 7 and 8.

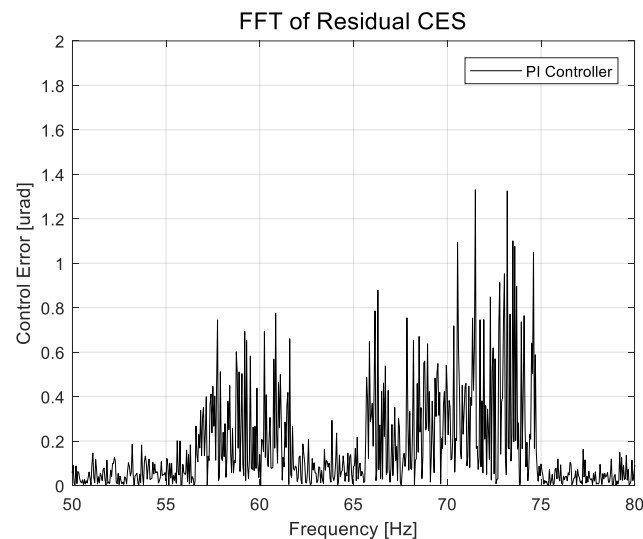


Figure 6. Power spectrum for analysis of uncompensated CES.

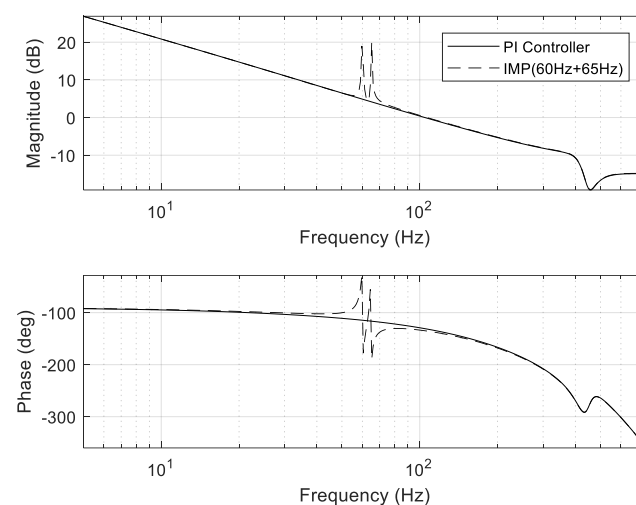


Figure 7. Open-loop transfer function of IMP-based controller (at 60 and 65 Hz).

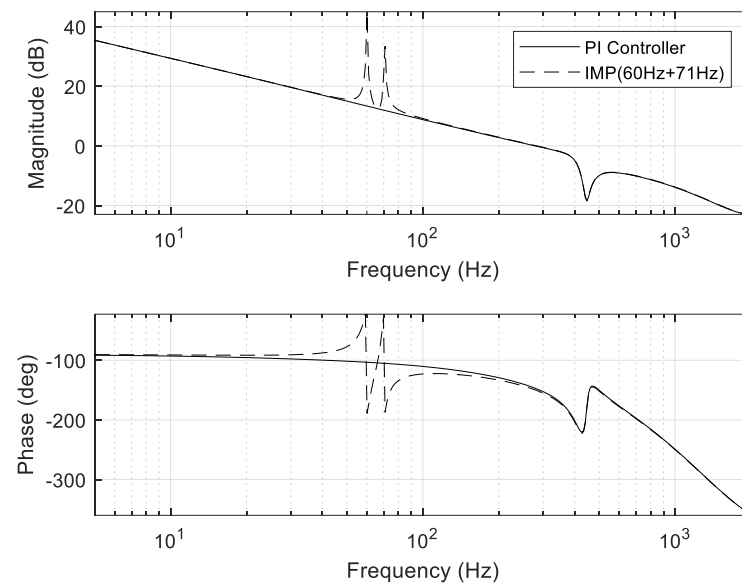


Figure 8. Open-loop transfer function of IMP-based controller (at 60 and 71 Hz).

As illustrated in Figure 4, the phase angles of the disturbance-attenuation performances at $\omega_1 = 60$ Hz, $\omega_2 = 65$ Hz, and $\omega_3 = 71$ Hz are estimated as $\phi_1 = 80^\circ$, $\phi_2 = 78^\circ$, and $\phi_3 = 77^\circ$, respectively. The IMP-based control input $u(k)$ can be defined utilizing the control law expressed in Equation (6). These phase values for cancellation frequencies can be used from the adaptation law, which is expressed in Equations (7) and (8). As depicted in Figures 7 and 8, the adaptive gain g of the IMP-based controller should be selected experimentally to maximize the stability of the control system in this study, and g is set to 2×10^{-4} . Consequently, the control performance of the IMP-based controller for disturbance attenuation is over 20 dB greater than that of the PI controller for a few frequency components.

According to the experimental results of the PI controller for FSM control with and without the IMP-based AFC, the target rotational position was maintained successfully at $500 \mu\text{rad}$. Figure 6 shows that the power spectrum of the residual CES for the PI controller without the IMP-based controller was $7.97 \mu\text{rad}$. When we used the IMP-based controller at 60, 65, and 71 Hz in the FSM control system, the RMS values of the CES were 7.43, 7.17, and 6.05 μrad , respectively. Additionally, we applied the IMP-based controller to multiple frequency components. When the IMP-based controller was used at 60 and 65 Hz in the FSM control system, the RMS value of the CES was 6.00 μrad . Furthermore, when the IMP-based controller was used at 60 and 71 Hz in the FSM control system, the RMS of the CES was 5.41 μrad , as illustrated in Figure 9a,b. These results indicated that the IMP-based controller was efficient at suppressing periodic disturbances in the FSM system, as shown in Table 2.

Table 2. Overall experimental results of FSM control system using IMP.

Specification		PI Controller	IMP (60 Hz)	IMP (65 Hz)	IMP (71 Hz)	IMP (60/65 Hz)	IMP (60/71 Hz)
Only IMP	Control error ($\mu\text{rad rms}$)	7.97	7.43	7.17	6.05	6.00	5.41

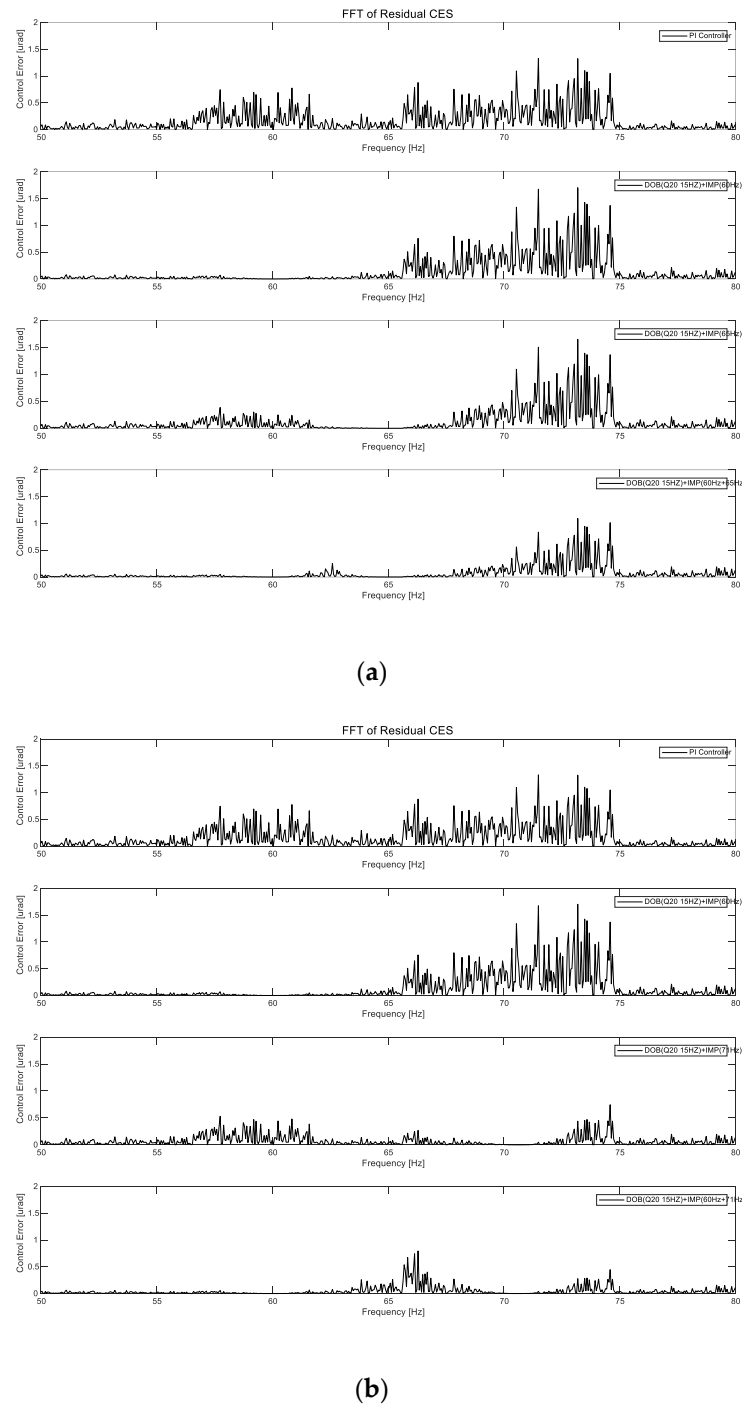


Figure 9. Experimental results of FSM control system: (a) IMP (at 60 and 65 Hz) and (b) IMP (at 60 and 71 Hz).

3.2. IMP-Based Controller with DOB

The design key of the IMP-based controller with DOB comes from the fact that it improves the disturbance-attenuation performance without redesigning the feedback controller. Theoretically, the IMP-based controller with DOB is designed for disturbance attenuation based on the nominal plant.

In general, the DOB is to use the inversed plant model to cancel the disturbance to the control system and then modify the control input to compensate. Also, the low-pass Q filter $Q(z)$ is applied to reduce high-frequency measurement noise and allow $Q(z) P_n^{-1}(z)$

to be realizable. Figure 10 presents a schematic diagram of the FSM control system using an IMP-based controller with DOB.

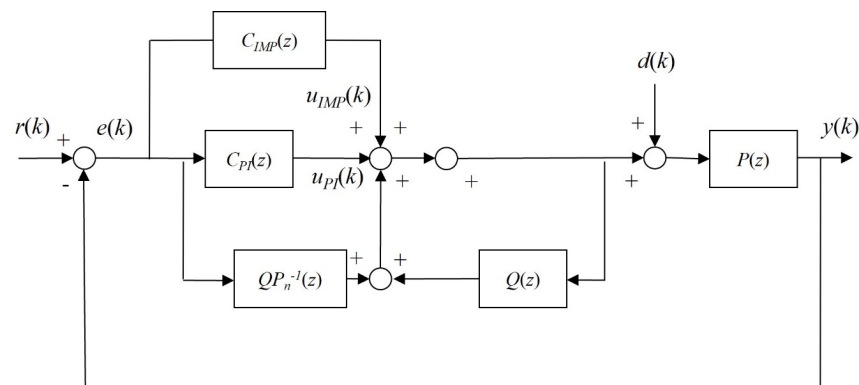
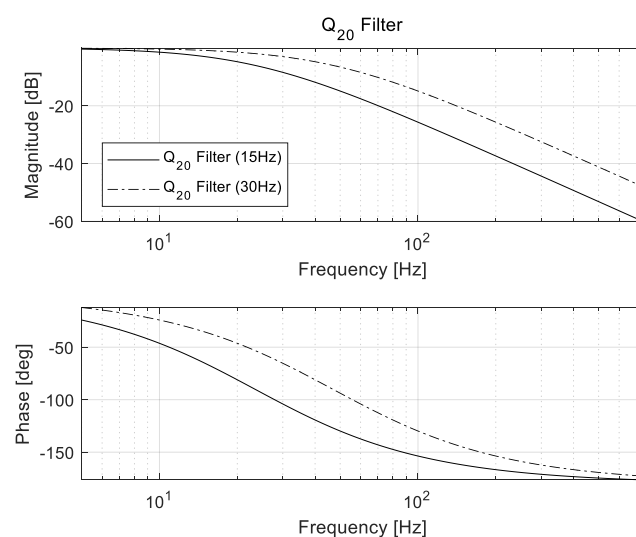


Figure 10. Schematic diagram of FSM control system using IMP-based controller with DOB.

In this study, the stability of the control system is related to the tunable coefficient and the order of the Q filter. Therefore, the tunable coefficient and order of the Q filter should be designed to improve the stability of the control system through the measurement data of the disturbance attenuation. Here, the Q_{20} and Q_{30} filters were utilized for the DOB-based controller for the FSM system, as illustrated in Figure 11. Via the analysis of the residual control-error signal (CES), which is the experimental result, the stability of the control system can be estimated. Consequently, utilizing Q_{20} and Q_{30} filters effectively improved the disturbance-suppression performances of the FSM control system. Moreover, the disturbance-suppression performances of the FSM motion system were effective in the low-frequency region with bandwidths of 15 and 30 Hz. The open-loop transfer functions of the aforementioned Q_{20} and Q_{30} filters with bandwidths of 15 and 30 Hz are expressed as follows:

$$Q_{20}(s) = \frac{1}{(\tau s + 1)^2} = \frac{1}{\tau^2 s^2 + 2\tau s + 1}, \quad (10)$$

$$Q_{30}(s) = \frac{1}{(\tau s + 1)^3} = \frac{1}{\tau^3 s^3 + 3\tau^2 s^2 + 3\tau s + 1}, \quad (11)$$



(a)

Figure 11. Cont.

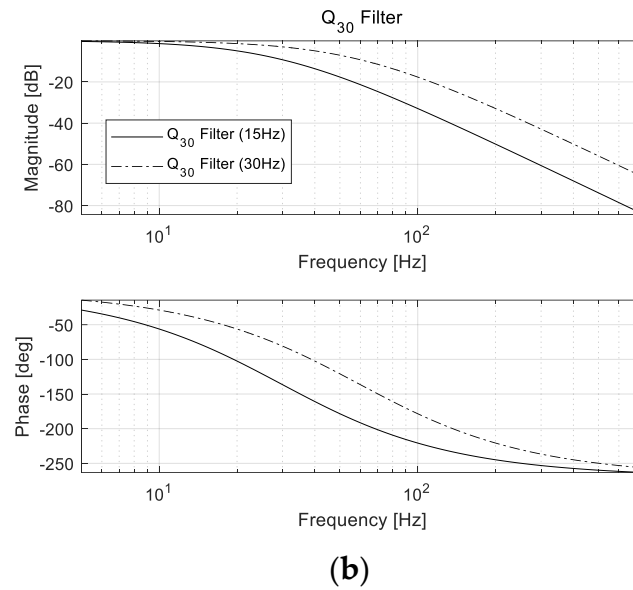


Figure 11. Open-loop transfer function Q filter for FSM control system: (a) Q_{20} and (b) Q_{30} .

The attenuation control performance of the FSM control system should be as high as possible in the frequency band of the disturbance applied to the system but not so high that it degrades the system's stability. Therefore, the loop gain of the FSM control system utilizing the IMP-based controller with DOB was selected to be higher than the loop gain of the IMP-only-based controller. Furthermore, as you increase the denominator order and bandwidth of the Q filter, the attenuation ping response of the FSM control system utilizing DOB is better. As the control performance, the open-loop transfer functions of the overall FSM control system utilized the IMP-based controller with DOB are illustrated in Figures 12–15. The open-loop transfer function of the FSM control system utilized by the IMP with the DOB can be obtained as follows:

$$G_{Total}(z) = \frac{(C_{IMP}(z) + C(z))P_n(z) + 1 - (1 - Q(z))}{(1 - Q(z))P_n(z)}, \quad (12)$$

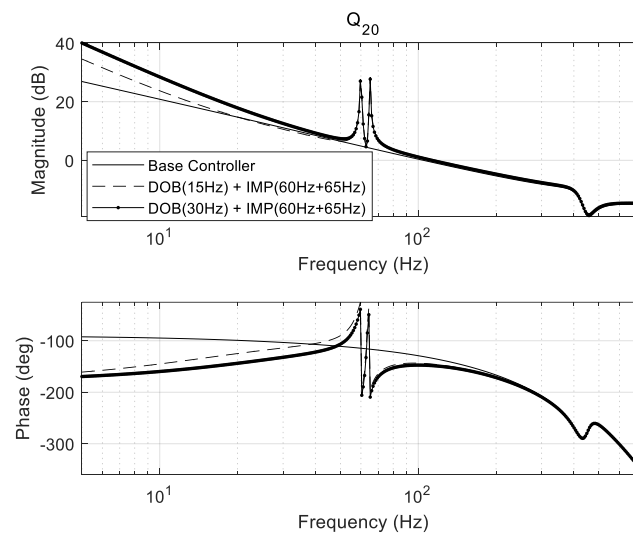


Figure 12. Open-loop transfer function of IMP-based controller (at 60 and 65 Hz) with DOB (Q_{20} filter).

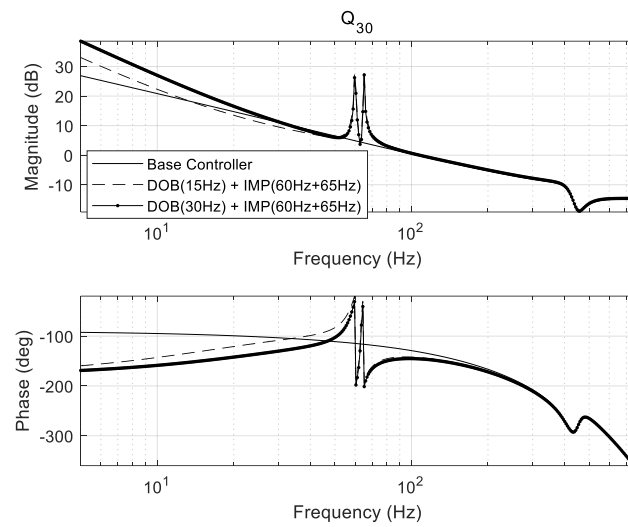


Figure 13. Open-loop transfer function of IMP-based controller (at 60 and 65 Hz) with DOB (Q_{30} filter).

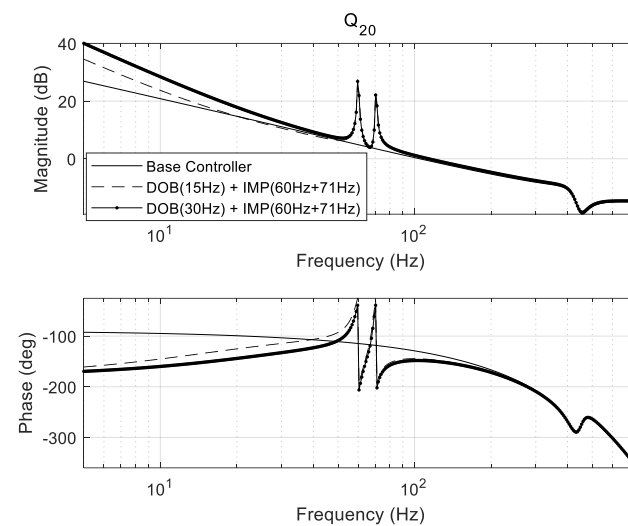


Figure 14. Open-loop transfer function of IMP-based controller (at 60 and 71 Hz) with DOB (Q_{20} filter).

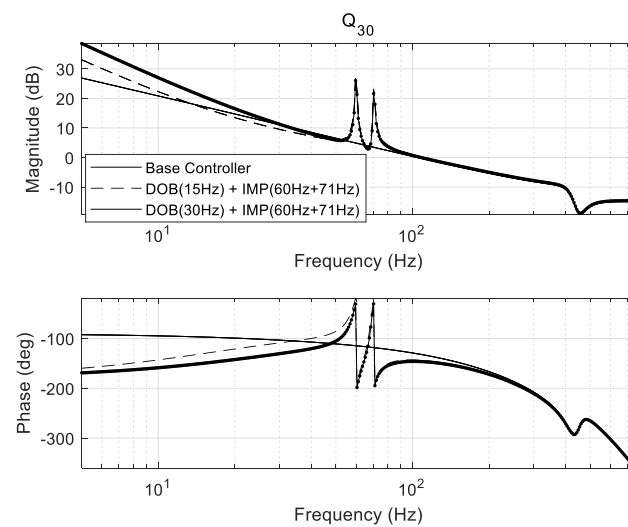


Figure 15. Open-loop transfer function of IMP-based controller (at 60 and 71 Hz) with DOB (Q_{30} filter).

4. Experimental Results of DOB-Based FSM Control System

In this study, we compared two main cases. First, in the IMP-based controller, the Q_{20} filter was used as the DOB. Second, in the IMP-based controller, the Q_{30} filter was used as the DOB. Moreover, the bandwidths of each of the binomial Q_{20} and Q_{30} filters were set to 15 Hz and 30 Hz. The target rotational position was successfully maintained at 500 μrad . As illustrated in Figure 15, the power spectrum of the residual CES of the IMP-based PI controller was 7.97 μrad . In the first case, when we used the IMP-based controller with the DOB (Q_{20} filter 15 Hz) at 60, 65, and 71 Hz in the FSM control system, the CES values were 6.96, 6.75, and 5.73 μrad , respectively, as illustrated in Figure 17a. When we used the IMP-based controller with the DOB (Q_{20} filter 30 Hz) at 60, 65, and 71 Hz in the FSM control system, the CES values were 6.76, 6.57, and 5.51 μrad , respectively, as illustrated in Figure 17b. In the second case, when we used the IMP-based controller with the DOB (Q_{30} filter 15 Hz) at 60 Hz, 65 Hz, and 71 Hz in the FSM control system, the CES values were 6.49, 6.28, and 5.36 μrad , respectively, as depicted in Figure 17c. When we used the IMP-based controller with the DOB (Q_{30} filter 30 Hz) at 60, 65, and 71 Hz in the FSM control system, the CES values were 6.18, 6.05, and 5.24 μrad , respectively, as depicted in Figure 17d.

To enhance the control attenuation performance of the FSM system, we applied the IMP-based controller with multiple frequency components. For the IMP-based controller with a Q_{20} filter having bandwidths of 15 and 30 Hz as the DOB, respectively, the CES values were 5.51 and 5.57 μrad , respectively. For the IMP-based controller with a Q_{30} filter having bandwidths of 15 and 30 Hz as the DOB, the CES values were 5.36 and 5.24 μrad , respectively, as depicted in Figure 17a–d. These results indicated that the performance of the IMP-based controller with the DOB was efficient in terms of suppressing periodic disturbances in the FSM system [38,39].

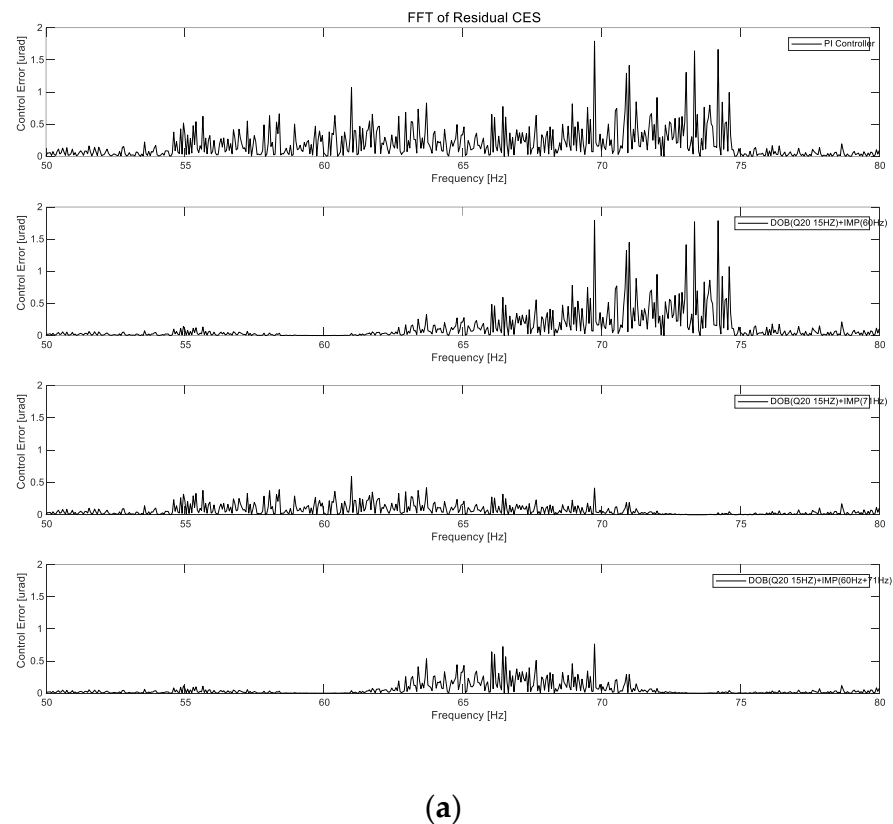
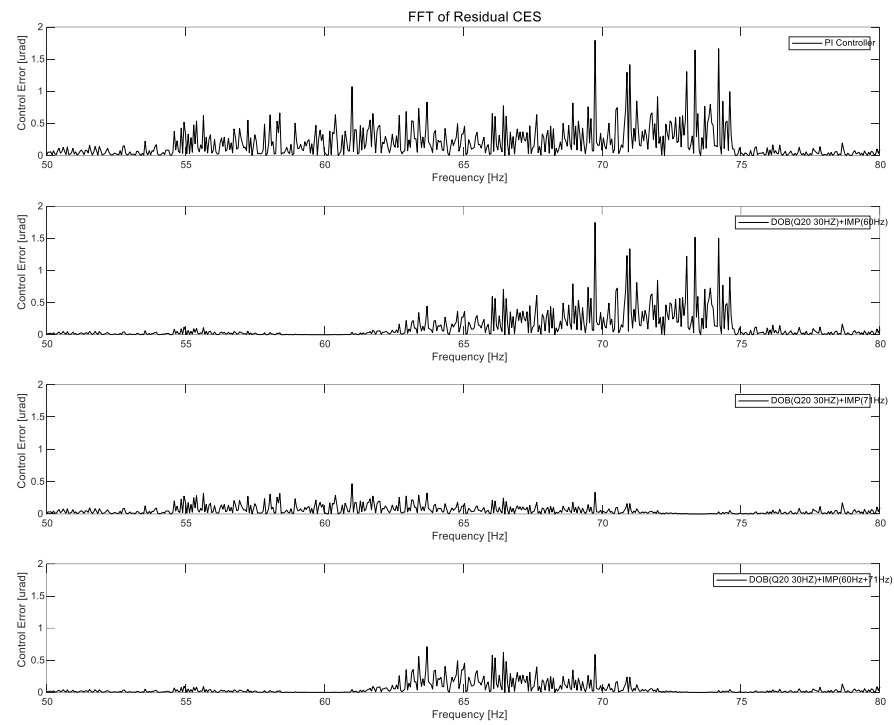
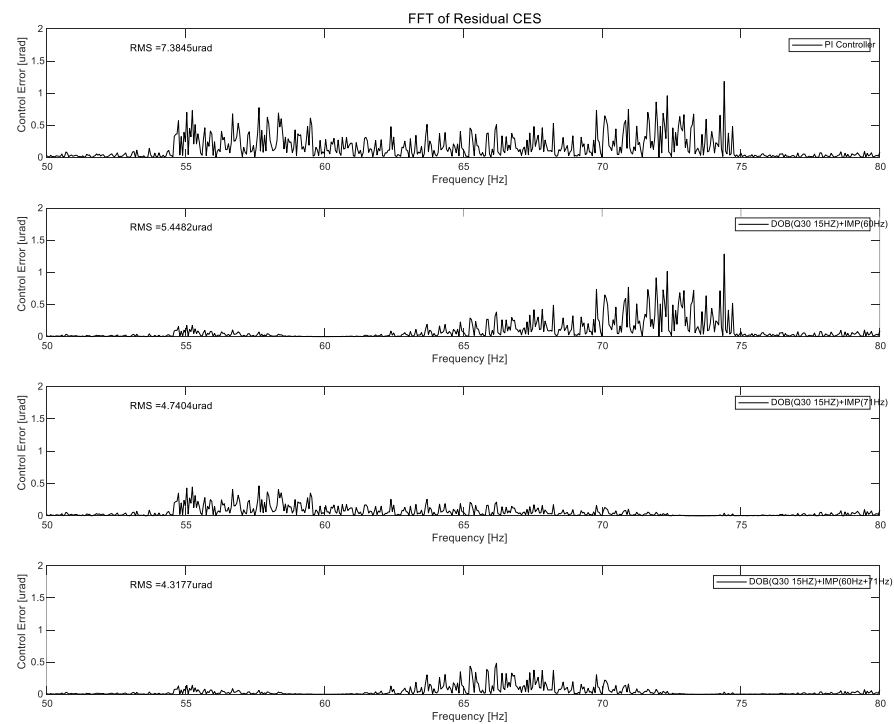


Figure 16. Cont.



(b)



(c)

Figure 17. Cont.

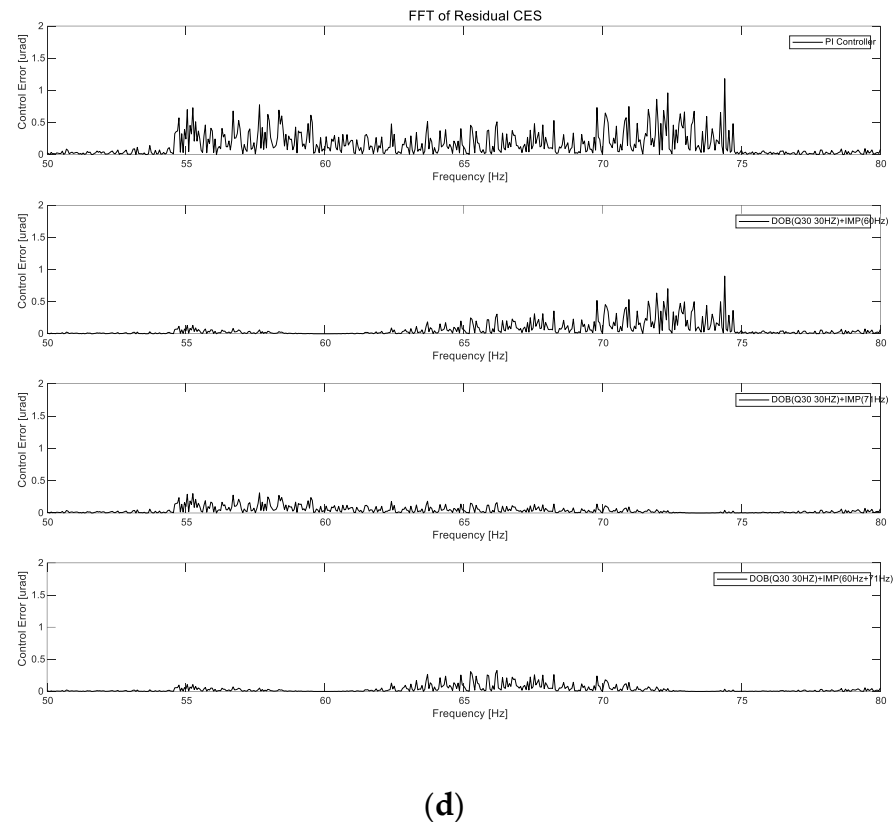


Figure 17. Experimental results of FSM control system when using IMP with DOB: (a) Q_{20} (15 Hz), (b) Q_{20} (30 Hz), (c) Q_{30} (15 Hz), and (d) Q_{30} (30 Hz).

5. Conclusions

In this study, we improved the disturbance-attenuation performance of an FSM control system by using an IMP-based controller with DOB to improve the control performance.

When the IMP-based controller with DOB (Q_{20} filter 15 Hz) was used at 60, 65, and 71 Hz, the CES values decreased by approximately 12.67, 15.3, and 28.1%, respectively, compared to those when using the IMP-based controller alone. When the IMP-based controller with DOB (Q_{20} filter 30 Hz) was used at 60, 65, and 71 Hz, the CES values decreased by approximately 15.1, 17.5, and 30.9%, respectively, compared to those when using the IMP-based controller alone. When the IMP-based controller with DOB (Q_{30} filter 15 Hz) was used at 60, 65, and 71 Hz, the CES values decreased by approximately 18.5, 21.1, and 32.8%, respectively, compared to those when using the IMP-based controller alone. When the IMP-based controller with DOB (Q_{30} filter 30 Hz) was used at 60, 65, and 71 Hz, the CES values decreased by approximately 22.4, 24.1, and 34.2%, respectively, compared to those when using the IMP-based controller alone.

Furthermore, to improve the disturbance-attenuation performance of the FSM control system by using an IMP-based controller with DOB, the IMP-based controller was set to have multiple frequency components. As summarized in Table 3, when we used the IMP-based controller with DOB, the CES values were lower than those obtained when using the IMP-based controller alone. These results indicated that the performance of the proposed controller was superior to that observed in a previous study of FSM control systems.

Table 3. Overall experimental results of FSM control system using IMP with and without DOB.

Specification		PI Controller	IMP (60 Hz)	IMP (65 Hz)	IMP (71 Hz)	IMP (60/65 Hz)	IMP (60/71 Hz)
Only IMP			7.43	7.17	6.05	6.00	5.41
Q ₂₀ filter (15 Hz)	Control error (μ rad rms)	7.97	6.96	6.75	5.73	5.51	5.21
Q ₂₀ filter (30 Hz)			6.76	6.57	5.51	5.57	5.06
Q ₃₀ filter (15 Hz)			6.49	6.28	5.36	5.04	4.82
Q ₃₀ filter (30 Hz)			6.18	6.05	5.24	5.12	4.84

Funding: This work was supported by an Agency for Defense Development (ADD) grant funded by the Government of the Republic of Korea in 2024.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The author declares no conflicts of interest.

References

- Sun, C.; Ding, Y.; Wang, D.; Tian, D. Backscanning step and stare imaging system with high frame rate and wide coverage. *Appl. Opt.* **2015**, *54*, 4960–4965. [[CrossRef](#)] [[PubMed](#)]
- Chen, N.; Potsaid, B.; Wen, J.T.; Barry, S.; Cable, A. Modeling and control of a fast steering mirror in imaging applications. In Proceedings of the 2010 IEEE International Conference on Automation Science and Engineering, Toronto, ON, Canada, 21–24 August 2010; pp. 27–32.
- Park, J.H.; Lee, H.S.; Lee, J.H.; Yun, S.N.; Ham, Y.B.; Yun, D.W. Design of a piezoelectric-driven tilt mirror for a fast laser scanner. *Jpn. J. Appl. Phys.* **2012**, *51*, 09MD14. [[CrossRef](#)]
- Liu, W.; Yao, K.; Huang, D.; Lin, X.; Wang, L.; Lv, Y. Performance evaluation of coherent free space optical communications with a double-stage fast-steering-mirror adaptive optics system depending on the Greenwood frequency. *Opt. Exp.* **2016**, *24*, 13288–13302. [[CrossRef](#)] [[PubMed](#)]
- Wang, C.; Hu, L.; Xu, H.; Wang, Y.; Li, D.; Wang, S.; Mu, Q.; Yang, C.; Cao, Z.; Lu, X.; et al. Wavefront detection method of a single-sensor based adaptive optics system. *Opt. Exp.* **2015**, *23*, 21403–21414. [[CrossRef](#)] [[PubMed](#)]
- Ye, D.; Li, S.; Yan, Z.; Zhang, Z.; Liu, Y. A new method for incoherent combining of far-field laser beams based on multiple faculae recognition. In *Young Scientists Forum*; SPIE: Bellingham, WA, USA, 2017; Volume 10710, p. 1071034.
- Loney, G.L. Design of a small-aperture steering mirror for high-bandwidth acquisition and tracking. *Opt. Eng.* **1990**, *29*, 1360–1365. [[CrossRef](#)]
- Merritt, P.H.; Albertine, J.R. Beam control for high-energy laser devices. *Opt. Eng.* **2013**, *52*, 021005. [[CrossRef](#)]
- Wood, G.L.; Perram, G.P.; Marciniak, M.A.; Goda, M. High-energy laser weapons: Technology overview. In Proceedings of the Proc. SPIE 5414, Laser Technologies for Defense and Security, Orlando, FL, USA, 12 April 2004; pp. 1–25.
- Meline, M.E.; Harrell, J.P.; Lohnes, K.A. Universal beam steering mirror design using the cross blade flexure. *Proc. SPIE* **1697**, 1992, 424–443.
- Dong, W.; Tang, J.; ElDeeb, Y. Design of dual-stage actuation system for high precision optical manufacturing. *Proc. SPIE* **2008**, 6928, 692828.
- Schellekens, P.; Rosielle, N.; Vermeulen, H.; Vermeulen, M.; Wetzels, S.; Pril, W. Design for precision: Current status and trends. *CIRP Ann.* **1998**, *47*, 557–586. [[CrossRef](#)]
- Ghai, D.P.; Venkatesh, A.; Swami, H.R.; Kumar, A. Large aperture, tip tilt mirror for beam jitter correction in high power lasers. *Def. Sci. J.* **2013**, *63*, 606–610. [[CrossRef](#)]
- Kluk, D.J.; Boulet, M.T.; Trumper, D.L. A high-bandwidth, high-precision, two-axis steering mirror with moving iron actuator. *Mechatronics* **2012**, *22*, 257–270. [[CrossRef](#)]
- Li, D.; Wu, T.; Ji, Y.; Li, X. Model analysis and resonance suppression of wide-bandwidth inertial reference system. *Nanotechnol. Precis. Eng.* **2019**, *2*, 177–187. [[CrossRef](#)]
- Gu, G.Y.; Zhu, L.M.; Su, C.Y.; Ding, H.; Fatikow, S. Modeling and control of piezo-actuated nan positioning stages: A survey. *IEEE Trans. Auto. Sci. Eng.* **2016**, *13*, 313–332. [[CrossRef](#)]
- Ling, J.; Feng, Z.; Ming, M.; Xiao, X. Damping controller design for nanopositioners: A hybrid reference model matching and virtual reference feedback tuning approach. *Int. J. Precis. Eng. Manuf.* **2018**, *19*, 13–22. [[CrossRef](#)]
- Wadikhaye, S.P.; Yong, Y.K.; Bhikkaji, B.; Moheimani, S.R. Control of a piezoelectrically actuated high-speed serial-kinematic AFM nanopositioner. *Smart Mater. Struct.* **2014**, *23*, 025030. [[CrossRef](#)]

19. Schitter, G.; Thurner, P.J.; Hansma, P.K. Design and input-shaping control of a novel scanner for high-speed atomic force microscopy. *Mechatronics* **2008**, *18*, 282–288. [\[CrossRef\]](#)
20. Gu, G.Y.; Zhu, L.M.; Su, C.Y. Integral resonant damping for high-bandwidth control of piezoceramic stack actuators with asymmetric hysteresis nonlinearity. *Mechatronics* **2014**, *24*, 367–375. [\[CrossRef\]](#)
21. McEver, M.A.; Cole, D.G.; Clark, R.L. Adaptive feedback control of optical jitter using Q-parameterization. *Opt. Eng.* **2004**, *43*, 904–910. [\[CrossRef\]](#)
22. Wang, G.; Chen, G.; Bai, F. High-speed and precision control of a piezoelectric positioner with hysteresis, resonance and disturbance compensation. *Microsyst. Technol.* **2016**, *22*, 2499–2509. [\[CrossRef\]](#)
23. Kempf, C.; Messner, W.; Tomizuka, M.; Horowitz, R. A comparison of four discrete-time repetitive control algorithms. In Proceedings of the American Control Conference (ACC), Chicago, IL, USA, 24–26 June 1992; pp. 2700–2704.
24. Tomizuka, M.; Tsao, T.C.; Chew, K.K. Analysis and synthesis of discrete-time repetitive controllers. *ASME J. Dyn. Syst. Meas. Contr.* **1989**, *111*, 353–358. [\[CrossRef\]](#)
25. Glück, M.; Pott, J.U.; Sawodny, O. Piezo-actuated vibration disturbance mirror for investigating accelerometer-based tip-tilt reconstruction in large telescopes. *IFAC Pap.* **2016**, *49*, 361–366.
26. Chao, D.; Mao, Y.; Ren, G. MEMS Inertial Sensors-Based Multi-Loop Control Enhanced by Disturbance Observation and Compensation for Fast Steering Mirror System. *Sensors* **2016**, *11*, 1920. [\[CrossRef\]](#)
27. Li, X.; Chen, S.L.; Teo, C.S.; Tan, K.K. An iterative data-based approach to disturbance observer sensitivity shaping. In Proceedings of the IECON 2016–42nd Annual Conference of the IEEE Industrial Electronics Society, Florence, Italy, 23–26 October 2016; pp. 6067–6072.
28. Ohishi, K.; Ohde, H. Collision and force control for robot manipulator without force sensor. In Proceedings of the 20th Annual Conference of IEEE Industrial Electronics, Bologna, Italy, 5–9 September 1994; Volume 2, pp. 766–771.
29. Umeno, T.; Hori, Y. Robust speed control of DC servomotors using modern two degrees-of-freedom controller design. *IEEE Trans. Ind. Electron.* **2002**, *38*, 363–368. [\[CrossRef\]](#)
30. Kim, B.K.; Chung, W.K.; Youm, Y. Robust learning control for robot manipulators based on disturbance observer. In Proceedings of the 22nd International Conference on Industrial Electronics, Control, and Instrumentation, Taipei, Taiwan, 9 August 1996; pp. 1276–1282.
31. Ishikawa, J.; Tomizuka, M. Pivot friction compensation using an accelerometer and a disturbance observer for hard disk. *IEEE/ASME Trans. Mechatron.* **1998**, *3*, 194–201. [\[CrossRef\]](#)
32. Huang, Y.H.; Massner, W. A novel disturbance observer design for magnetic hard drive servo system with rotary actuator. *IEEE Trans. Magn.* **1998**, *34*, 1892–1894. [\[CrossRef\]](#)
33. Wang, L.; Su, J.; Xiang, G. Robust motion control system design with scheduled disturbance observer. *IEEE Trans. Ind. Electron.* **2016**, *63*, 6519–6529. [\[CrossRef\]](#)
34. Chen, W.H.; Yang, J.; Guo, L.; Li, S. Disturbance-observer-based control and related methods—An overview. *IEEE Trans. Ind. Electron.* **2016**, *63*, 1083–1095. [\[CrossRef\]](#)
35. Tang, T.; Ma, J.; Ge, R. PID-I controller of charge coupled device-based tracking loop for fast-steering mirror. *Opt. Eng.* **2011**, *50*, 043002. [\[CrossRef\]](#)
36. Lee, H.S.; Tomizuka, M. Robust motion controller design for high-accuracy positioning systems. *IEEE/ASME Trans. Mechatron.* **2000**, *2*, 32–38.
37. White, M.; Tomizuka, M.; Smith, C. Improved track following in magnetic disk drives using a disturbance observer. *IEEE/ASME Trans. Mechatron.* **2000**, *5*, 3–11. [\[CrossRef\]](#)
38. Nam, B.U.; Gimm, H.; Kang, D.; Gweon, D. Design and analysis of a tip-tilt guide mechanism for the fast steering of a large-scale mirror. *Opt. Eng.* **2016**, *55*, 106120. [\[CrossRef\]](#)
39. Nam, B.U.; Gimm, H.; Kim, J.G.; Kim, G.T.; Kim, B.U. Development of a fast steering mirror of large diameter. In *Integrated Photonics: Materials, Devices, and Applications IV*; SPIE: Bellingham, WA, USA, 2017; Volume 10249, p. 102490R.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.