Sudden Disturbance Suppression Control Considering Constraints for High-Precision Stage Using Reference Governor

Yuma Yazaki[1], Hiroshi Fujimoto[1]

***Abstract*— Reference Governor (RG) is a control method used in add-on control schemes in closed-loop systems to supervise reference signals and enforce constraints. Although previous studies of RG have mainly discussed a command tracking performance, a disturbance suppression performance has been rarely discussed. This paper proposes a novel control method based on RG to suppress the effect of sudden disturbance. Simulations and experiments are performed to demonstrate the effectiveness of the proposed method.**

I. INTRODUCTION

A high-precision stage is an essential piece of industrial equipment for producing semiconductors and liquid crystal displays. The stage demands high throughput and high precision because the products made by the stage should be of a low price and high space density. Several studies on the design of controllers with high feedback (FB) bandwidth are reported in the literature. For example, a dual-servo stage, which has coarse and fine components [1], [2], or the miniaturization of an actuator of the stage [3], [4]. However, actuator miniaturization leads to thrust saturation. In addition, the dual-servo stage has to be controlled so as not to violate gap limitation between the fine and coarse parts, or a relative velocity limitation. Hence, designing a control system keeping these constraints in mind is important.

In addition, a two-degrees-of-freedom control that combines feedforward (FF) and FB control is widely used in a trajectory tracking control for a high-precision stage. The FF control is mainly used to improve the tracking performance [5]. In our previous study, we proposed a control method considering thrust limitations in the FF control framework [6]. On the other hand, the FB controller is usually designed to optimize its performance related to suppression of disturbance that is analyzed and expected in advance [7]. In this case, the controller achieves good suppression of expected disturbances. However, performance related to the suppression of sudden and unexpected disturbances may degrade because of actuator saturation. Therefore, the FB controller should be able to manage not only expected disturbances but also sudden disturbances.

For this reason, this paper proposes a suppression control method for sudden disturbances based on model predictive control (MPC) and RG. The block diagram of RG is shown in Fig. 1. The proposed method makes it possible to improve the disturbance suppression performance within the constraints by modifying the reference signals properly.

[1]The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba, 277-8561, Japan, yazaki@hflab.k.u-tokyo.ac.jp, fujimoto@k.u-tokyo.ac.jp

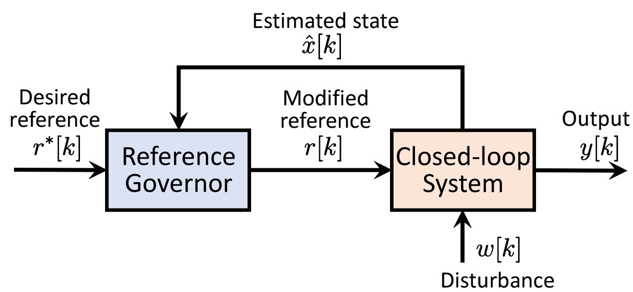


Fig. 1. Block diagram of reference governor.

Several notable studies have focused on RG: Scalar Reference Governor (SRG) [8], [9], Command Governor (CG) [10], [11], Extended Command Governor (ECG) [12], [13], MPC-based RG [14]. These studies mainly discuss the tracking performance to a constant reference signal and do not discuss the disturbance suppression performance. Hatanaka and Takaba [15] proposed an RG considering with step disturbances. However, their study does not discuss disturbance suppression performance. Moreover, the method is markedly influenced by a modeling error because it calculates the modified reference signals when it is off-line.

RG has not been experimentally verified extensively in previous studies because of its high calculation cost. The method proposed in this paper can verify its effectiveness experimentally by partly using the implementation proposed in [9]. Furthermore, this paper discusses the disturbance suppression performance of the proposed method, which has not been paid attention to in the previous studies of RG. Therefore, our method gives a new perspective in this field.

The outline of this paper is as follows. Section II proposes a disturbance suppression control by shaping the reference signals based on MPC. In section III, a disturbance suppression control method by modifying the reference signals based on RG and considering the constraints is proposed. Finally, section IV demonstrates the effectiveness of the proposed method through experiments.

II. Disturbance suppression control by shaping reference signals based on model predictive control without constraints

In this section, we introduce the disturbance suppression control method by shaping reference signals based on MPC without constraints. Several previous studies proposed reference shaping methods using MPC, however, this is the first study in which mainly forcuses on the disturbance supression performance. This paper supposes an impulse input disturbance as the sudden disturbance.

A. Impulse input disturbance response

This section gives basic information on an impulse input disturbance response and the concept of the proposed method. In motion control, the controller often has more than one integrator to avoid steady-state errors by step-input disturbances. When an impulse input disturbance is added to such a controller, it is well known that the error $e(t)$ satisfies the following relationship [16].

$$\int_0^\infty e(t)dt = 0 \tag{1}$$

Here, $e(t) = r(t) - y(t)$, $r(t)$ is the reference signal and $y(t)$ is the plant output.

Therefore, the impulse input disturbance response makes the integrated value of the error zero as shown in Fig. 2(a). The shape of the response waveform itself cannot be changed because the relationship shown in (1) is always held to the impulse input disturbance even if the FB bandwidth of the controller is improved.

Therefore, when we modify the original reference signals, the error between the modified reference and the plant output satisfies the relationship shown in (1). However, the original reference signals are not related to the plant output. Hence, the response waveform can be improved by managing the reference signals properly. In other words, the proposed method is a control method that interchanges the relationship between the reference signal and the plant output in a normal control system. The conceptual diagram of the impulse input disturbance response by modifying the reference signal is shown in Fig. 2(b). This paper discusses impulse disturbance suppression control by management of reference signals.

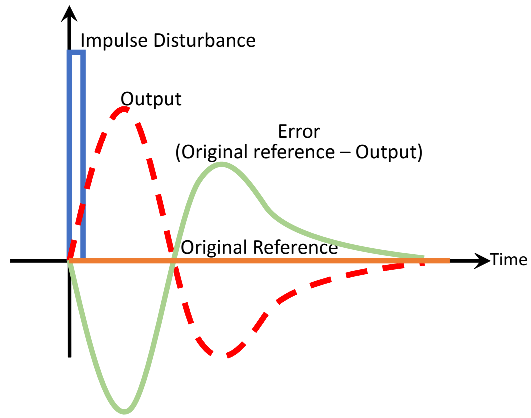
B. Modification of reference signals based on MPC without constraints

This paper considers a discrete-time servo system given by

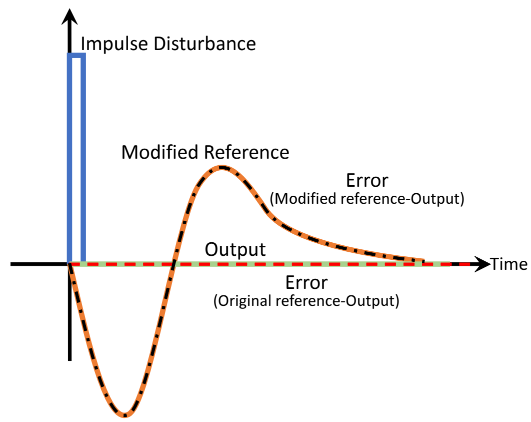
$$\begin{aligned} \boldsymbol{x}[k+1] &= \boldsymbol{A}\boldsymbol{x}[k] + \boldsymbol{B}r[k],\ \boldsymbol{x}[0] = \boldsymbol{x}_0, \\ y[k] &= \boldsymbol{C}\boldsymbol{x}[k], \end{aligned} \tag{2}$$

where $\boldsymbol{x} \in \mathbf{R}^n$ is the closed loop state, $y \in \mathbf{R}^1$ is the output to be controlled, and $r \in \mathcal{R} = [r_{\min}, r_{\max}] \subseteq \mathbf{R}^1$ is the reference input of the closed system. $\boldsymbol{A}$ is assumed to be a stable matrix in this paper. Then, the $i\,(i \geq 1)$ samples after the state space is estimated as follows:

$$\begin{aligned} \hat{\boldsymbol{x}}[k+i] &= \boldsymbol{A}^i\boldsymbol{x}[k] + \sum_{j=0}^{i-1} \boldsymbol{A}^{i-j-1}\boldsymbol{B}r[k+j] \\ \hat{y}[k+i] &= \boldsymbol{C}\boldsymbol{A}^i\boldsymbol{x}[k] + \boldsymbol{C}\sum_{j=0}^{i-1} \boldsymbol{A}^{i-j-1}\boldsymbol{B}r[k+j] \end{aligned} \tag{3}$$



(a) General input impulse disturbance response.



(b) Input impulse disturbance response by modifying reference signal.

Fig. 2. Impulse input disturbance response. It becomes possible to manage the shape of response itself by modifying the original reference signal as shown in Fig. 2(b).

Thus, the error between the original reference signal r^* and the plant output at $k+i$ is estimated as

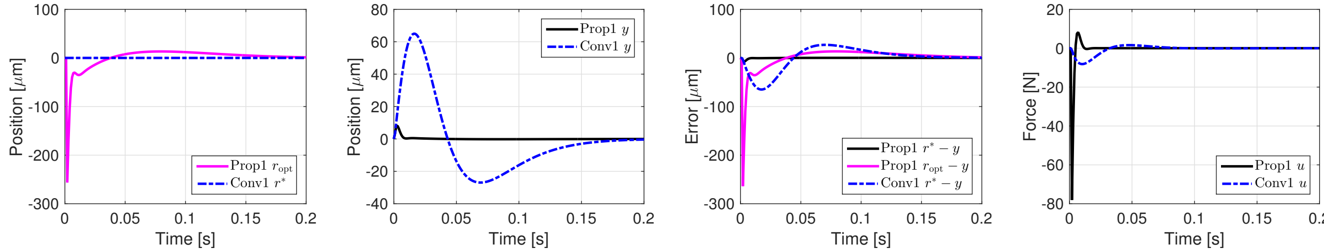
$$\begin{aligned} \hat{e}[k+i] &= r^* - \hat{y}[k+i] \\ &= r^* - \left(\boldsymbol{C}\boldsymbol{A}^i\boldsymbol{x}[k] + \boldsymbol{C}\sum_{j=0}^{i-1} \boldsymbol{A}^{i-j-1}\boldsymbol{B}r[k+j]\right). \end{aligned} \tag{4}$$

When the reference input r is assumed to be constant in the predictive horizon, namely $r[k+j] = r (0 \leq j \leq i-1)$, the error is represented as

$$\hat{e}[k+i] = r^* - \left(\boldsymbol{C}\boldsymbol{A}^i\boldsymbol{x}[k] + \sum_{j=0}^{i-1} \boldsymbol{C}\boldsymbol{A}^j\boldsymbol{B}r\right). \tag{5}$$

Here, the order of $\hat{e}[k+i]$ is at most 1st to r because r^* is given in advance and $\boldsymbol{x}[k]$ can be measured for each sampling time. Now a performance index is set as follows:

$$\begin{aligned} J &= ||\hat{\boldsymbol{e}}_{i-1}||_2^P + ||\hat{e}[k+i]||_2^Q, \\ \hat{\boldsymbol{e}}_h &= \begin{bmatrix} \hat{e}[k] \\ \hat{e}[k+1] \\ \vdots \\ \hat{e}[k+h] \end{bmatrix},\ h \in \mathrm{Z}_+. \end{aligned} \tag{6}$$



(a) Reference command. (b) Plant output. (c) Position error. (d) Controller output.

Fig. 3. Simulation results of disturbance suppression control by reference command modification based on MPC.

$||\hat{\boldsymbol{e}}_{i-1}||_2^P$ and $||\hat{e}[k+i]||_2^Q$ represent the integral square value of the error and the final state value of the error, respectively. Then, the performance index is represented as a quadratic function of r. An optimal value of the performance index r_{opt} is derived as (7) when the performance index is represented in $J = p_2(\boldsymbol{x}[k], r^*)r^2 + p_1(\boldsymbol{x}[k], r^*)r + p_0(\boldsymbol{x}[k], r^*)$.

$$r_{\text{opt}} = -\frac{p_1(\boldsymbol{x}[k], r^*)}{2p_2(\boldsymbol{x}[k], r^*)} \tag{7}$$

It is expected that the impulse input disturbance response is improved by using r_{opt} calculated for each time as the new reference signals.

C. Simulation 1

This section demonstrates the effectiveness of the modification of reference signals based on MPC by simulation results. This simulation is conducted for the impulse disturbance suppression performance when setting the original reference signal and an initial state of the closed-loop system as $r^* = 0$ and $\boldsymbol{x}[0] = \boldsymbol{O}$, respectively. The "Conventional 1" method does not modify the original reference signal. The "Proposed 1" method uses the optimal reference signal r_{opt} derived from the method proposed in section IIB as the reference signal. In addition, a plant model $P(s)$ is defined as a rigid body model shown in (8) in this paper.

$$P(s) = \frac{1}{M_p s^2},\ M = 14.0\,\text{kg} \tag{8}$$

Here, M_p is a mass. The control period is $T_s = 1.0$ ms and a PID position controller is designed for the plant so that the closed-loop bandwidth of the position loop is 10 Hz. This paper assumes that the following impulse–shaped disturbance is added.

$$w(t) = \begin{cases} 100\,\text{N}, & 0 \le t \le T_s \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

In this simulation, the performance index is defined as follows:

$$J = ||\hat{\boldsymbol{e}}_i||_2\,, \tag{10}$$

where, the predictive horizon is $i = 3$.

The simulation results are shown in Fig. 3. As shown in Fig. 3(b), "Conventional 1" needs a long time to converge the disturbance response because the error between the original reference signal and the plant output satisfies the relationship shown in (1). On the other hand, in "Proposed 1", the convergence of the error to the original reference signals is considerably improved by satisfying the relationship (1) to the error between the modified reference signals and the plant output. In this paper, the settling time is defined as the time from adding the impulse disturbance to when the position error is smaller than 1 μm. The settling time of "Conventional 1" and "Proposed 1" are 177 ms and 7.49 ms, respectively.

The suppression performance is largely improved. However, the controller output in "Proposed 1" is very large as shown in Fig. 3(d). Therefore, reference signal modification with controller output constraints is required.

III. Disturbance suppression control by shaping reference signals based on reference governor

The method proposed in section II shows that the signal modification can reduce the effect of the impulse input disturbance. However, this method gives large controller output. A disturbance suppression method considered with controller output limitation is needed because all real actuators have output constraints. This section proposes a reference signal modification method considering constraints based on RG.

A. Maximal output admissible set

This section explains a maximal output admissible set (MAS) which is widely used in the previous studies of RG [17]. To grasp the state of the control system for the constraints, it is important to modify the reference signals properly considering the constraints. A prescribed constraint set is a set of state space that consists of all state variables satisfying the constraints. In addition, a positively invariant set is a set that always keeps a state in it for any external input if the initial state is inside the set. An output admissible set is a common set of the prescribed constraint set and the positively invariant set, and MAS is its maximal set.

The closed-loop system always satisfies the constraint conditions when the initial state variables of the system are inside MAS. MAS depends on the reference signals and the current state variables. Most previous studies of RG select the proper MAS by managing the reference signals.

1) Linear discrete-time servo system with constraint: In addition to the linear discrete-time servo system shown in (2), a variable to consider constraints on state and input is

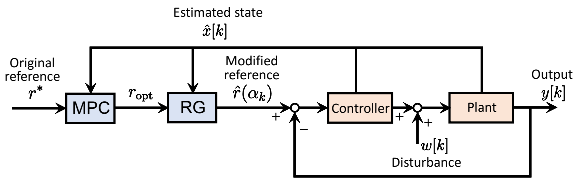


Fig. 4. Block diagram of the proposed method based on RG.

prepared by

$$\boldsymbol{z}[k] = \boldsymbol{L}\boldsymbol{x}[k] + \boldsymbol{D}r[k] \quad \in \mathcal{Z}(\xi) \subseteq \mathbf{R}^p, \tag{11}$$

where, $\boldsymbol{L} \in \mathbf{F}^{p\times n}$ and $\boldsymbol{D} \in \mathbf{F}^{p\times m}$. This paper assumes $\boldsymbol{O} \in \mathcal{Z}$ and $\mathcal{Z}$ is bounded. From these assumptions, $\mathcal{Z}(\xi) \in \mathbf{R}^p$ is defined as a polytope given by

$$\mathcal{Z} = \{\boldsymbol{z} \in \mathbf{R}^p | \boldsymbol{M}\boldsymbol{z} \le \boldsymbol{m}(\xi)\}. \tag{12}$$

In (12), the inequality is a component-wise inequality and $\xi \in \Xi$ is a variable characterizing constraints that is given when the control is started.

2) Difinition of MAS: This section defines MAS by (2) and (11). $\boldsymbol{x}[i;k,\boldsymbol{x}_0,\hat{r}]$ is a solution of (2) satisfying $\boldsymbol{x}[k] = \boldsymbol{x}_0$, $r[k+i] = \hat{r}$ for all $i \in \mathrm{Z}_+$, and $\boldsymbol{z}[i;k,\boldsymbol{x}_0,\hat{r}] = \boldsymbol{L}\boldsymbol{x}[i;k,\boldsymbol{x}_0,\hat{r}] + \boldsymbol{D}\hat{r}$. Then MAS Ω_∞ is defined as follows [17]:

$$\begin{aligned} \Omega_\infty(\mathcal{R},\Xi) = \{&(\boldsymbol{x}_0, r, \xi) : \boldsymbol{x}_0 \in \Omega_\infty(r,\xi), \\ &\text{for some}\,(r,\xi) \in \mathcal{R}\times\Xi\}, \\ \Omega_\infty(\hat{r},\xi) = \{&\boldsymbol{x}_0 : \boldsymbol{z}[i;k,\boldsymbol{x}_0,\hat{r}] \in \mathcal{Z}(\xi), \forall i \ge 0\}. \end{aligned} \tag{13}$$

By the definition, $\Omega_\infty(\hat{r},\xi)$ is a positively invariant set. This means that if $\boldsymbol{x}[k] = \boldsymbol{x}_0 \in \Omega_\infty(\hat{r},\xi)$ then $\boldsymbol{x}[k+i] \in \Omega_\infty(\hat{r},\xi)$ for all $i \in \mathcal{K}$. Furthermore, there is an integer $\hat{i}$ satisfying $\Omega_\infty(\hat{r},\xi) = \Omega_{\hat{i}}(\hat{r},\xi)$ for each $\hat{r} \in \mathcal{R}$ and $\xi \in \Xi$ because $\boldsymbol{A}$ is a stable matrix. This paper assumes there is an integer κ such that

$$\kappa = \sup_{\hat{r}\in\mathcal{R},\xi\in\Xi} \hat{\hat{i}}. \tag{14}$$

If κ can be obtained, MAS is given as follows:

$$\Omega_\infty(\hat{r},\xi) = \Omega_\kappa(\hat{r},\xi), \quad \forall\hat{r} \in \mathcal{R},\ \forall\xi \in \Xi. \tag{15}$$

In this paper, such the number of steps κ is calculated in advance. The calculation method of κ is described in [18] and this paper inserts $\boldsymbol{x}_{p0} = \boldsymbol{A}_p^{-1}\boldsymbol{b}_p w$ into an initial state of the plant to use the calculation method. Here, $\boldsymbol{A}_p$ and $\boldsymbol{b}_p$ are coefficients of a state $\boldsymbol{x}_p[k]$ and an input $u[k]$ in a discrete-time state equation of the plant $\boldsymbol{x}_p[k+1] = \boldsymbol{A}_p\boldsymbol{x}_p[k] + \boldsymbol{b}_p u[k]$.

3) Characterization of MAS: This section characterizes MAS to calculate it in real-time [9]. From (3) and (11), $\boldsymbol{z}[k+i]$ is given by

$$\begin{aligned} \boldsymbol{z}[k+i] &= \boldsymbol{L}\boldsymbol{A}^i\boldsymbol{x}[k] \\ &\quad + \boldsymbol{L}\sum_{j=0}^{i-1}\boldsymbol{A}^{i-j-1}\boldsymbol{B}r[k+j] + \boldsymbol{D}r[k+i]. \end{aligned} \tag{16}$$

Assuming $r[k+j] = \hat{r}\,(0 \le j \le i)$, from (12) and (16), the constraint at $k+i$ is represented as follows:

$$\boldsymbol{M}\boldsymbol{L}\boldsymbol{A}^i\boldsymbol{x}[k] + \boldsymbol{M}\left(\boldsymbol{L}\sum_{j=0}^{i-1}\boldsymbol{A}^j\boldsymbol{B} + \boldsymbol{D}\right)\hat{r} \le \boldsymbol{m}. \tag{17}$$

Let us define

$$\begin{aligned} &\boldsymbol{h}_{l,i} = \boldsymbol{M}_l\boldsymbol{L}\boldsymbol{A}^i,\ g_{l,i} = \boldsymbol{M}_l\left(\boldsymbol{L}\sum_{j=0}^{i-1}\boldsymbol{A}^j\boldsymbol{B} + \boldsymbol{D}\right), \\ &l \in \mathcal{L} = \{1,2,\cdots,q\},\ i \in \mathcal{K} = \{0,\cdots,\kappa\}. \end{aligned} \tag{18}$$

Then, by (13) and (18), MAS is characterized as follows:

$$\begin{aligned} \Omega_\kappa(\mathcal{R},\Xi) = \{&(\boldsymbol{x}_0,\hat{r},\xi) : \boldsymbol{h}_{l,i}\boldsymbol{x}_0 + g_{l,i}\hat{r} \le m_l(\xi), \\ &l \in \mathcal{L},\ i \in \mathcal{K},\ \hat{r} \in \mathcal{R},\ \xi \in \Xi\}. \end{aligned} \tag{19}$$

As a result, MAS can be represented by $q \times (\kappa+1)$ inequalities.

B. Design of RG

It is assumed that the state $\boldsymbol{x}$ of the closed-loop system can be observed. Then, $r[k] = \hat{r}(\alpha_k)$, which satisfies $\boldsymbol{x}[k] \in \Omega_\kappa(\hat{r}(\alpha_k),\xi)$ is calculated by

$$\hat{r}(\alpha_k) = (1-\alpha_k)\bar{r}_{\rm opt} + \alpha_k r_{\rm opt}. \tag{20}$$

Here, $\bar{r}_{\rm opt} = -\beta r_{\rm opt}\,(\beta > 0)$. $\hat{r}(\alpha_k)$ is the nearest value to the optimal solution $r_{\rm opt}$ satisfying the constraints when a maximal $\alpha_k \in [0,1]$ that satisfies $x[k] \in \Omega_\kappa(\hat{r}(\alpha_k),\xi)$ is selected. By (19), (20), $\boldsymbol{x}[k] \in \Omega_\kappa(\hat{r}(\alpha_k),\xi)$ holds if

$$\begin{aligned} \alpha_k g_{l,i}(r_{\rm opt} - \bar{r}_{\rm opt}) \le m_l(\xi) - \boldsymbol{h}_{l,i}\boldsymbol{x}[k] - g_{l,i}\bar{r}_{\rm opt}, \\ \forall l \in \mathcal{L}, \forall i \in \mathcal{K}. \end{aligned} \tag{21}$$

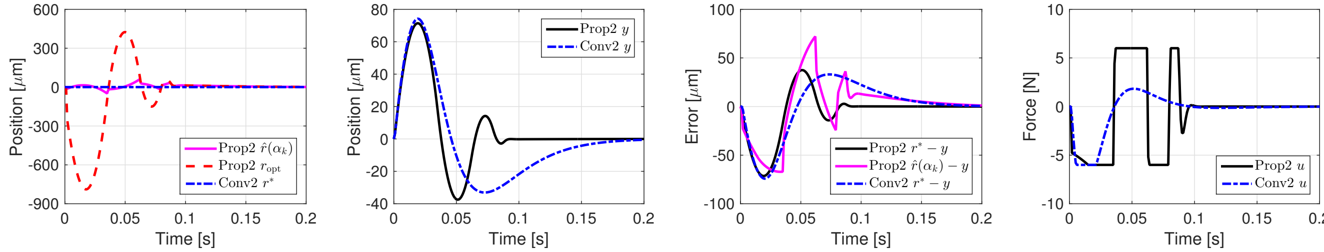
When $\boldsymbol{h}_{l,i}, g_{l,i}$ is calculated in advance, α_k is given as follows:

$$\begin{aligned} \alpha_k &= \min\{1,\tilde{\alpha}_k\}, \\ \tilde{\alpha}_k &= \min_{(l,i)\in\mathcal{L}\times\mathcal{K}} \frac{m_l(\xi) - \boldsymbol{h}_{l,i}\boldsymbol{x}[k] - g_{l,i}\bar{r}_{\rm opt}}{g_{l,i}(r_{\rm opt} - \bar{r}_{\rm opt})}. \end{aligned} \tag{22}$$

From these results, the real-time calculation of α_k becomes possible.

The above method of generation of the reference signals is often used in SRG. However, most previous studies of SRG assume that the modified reference signals have a monotonic property; that is, the reference signals increased or decreased monotonically. Therefore, in the case of coinciding the initial state of the plant with the original reference and discussing only the effect of the disturbance, it is impossible to modify the reference signals in response to the disturbance.

On the other hand, the proposed method can manage the reference signals that do not have the monotonic property by applying RG after using MPC. Thus, the proposed method can modify the reference signals properly in response to the disturbance. The block diagram of the proposed method based on RG is shown inFig. 4.



(a) Reference command. (b) Plant output. (c) Position error. (d) Controller output.

Fig. 5. Simulation results of disturbance suppression control by reference command modification based on RG.

C. Simulation 2

This section discusses the impulse disturbance suppression control based on RG. The simulation condition is the same as in section IIC and the limitation of the controller output is $u_{\rm lim} = 6.0\,{\rm N}$. "Conventional 2" does not modify the original reference signal and it applies an anti-windup compensation proposed in [19] to prevent the windup phenomenon by a controller saturation. "Proposed 2" uses the modified reference signal $\hat{r}(\alpha_k)$ derived from the method proposed in section IIIB as the reference signal. In this paper, $\beta = 10$.

The simulation results are shown in Fig. 5. The settling time of "Conventional 2" and "Proposed 2" are 185 ms and 89.2 ms, respectively. As shown in Fig. 5(a), "Proposed 2" can modify the reference signals that do not have the monotone property. As a result, the disturbance suppression performance in "Proposed 2" is improved while satisfying the constraints.

IV. Experimental verification

A. Experimental conditions

This experiment uses a high precision stage shown in Fig. 6(a). This stage is guided by an air guide and driven by a linear motor. The position of the stage is measured by a linear encoder whose resolution is $1\,{\rm nm}$ and the velocity is the difference of the position. The frequency response of the stage is shown in Fig. 6(b). The plant model is defined as a rigid body model shown in (8) by fitting the frequency response data. The PID position controller is designed for the plant, so that the closed-loop bandwidth of the position loop can be $10\,{\rm Hz}$. It is discretized by a Tustin transformation with the control period of $T_s = 1.0\,{\rm ms}$. The disturbance shown in (9) is added to the linear motor as softfare disturbance in the experiment.

This experiment is compared with four methods as shown in TABLE. I. The limitation of the controller output is $u_{\rm lim} = 6.0\,{\rm N}$. In "Conventional 2", the controller output constraint $u_{\rm lim}$ is given on the source program. In "Proposed 2", however, note that the controller output constraint $u_{\rm lim}$ is considered only when MAS is generated and is not given on the source program.

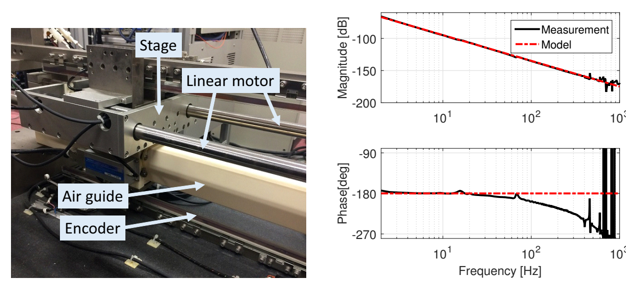
B. Experimental results

The result of comparison of "Conventional 1" and "Proposed 1" is shown in Fig. 7 and that of "Conventional 2" and "Proposed 2" is shown in Fig. 8. As shown in Fig. 7(b), the settling time of "Conventional 1" and "Proposed 1" are 198 ms and 17.1 ms, respectively. The disturbance suppression performance is also considerably improved in the experiment. Moreover, as shown in Fig. 8(b), the settling time of "Conventional 2" and "Proposed 2" are 167 ms and 112 ms, respectively. The disturbance suppression performance is improved within the constraints to modify the reference signal based on RG. From Fig. 8(d), it is found that RG can be calculated in real-time because the controller works within the constraint despite it being on the source program.

TABLE I

Four control methods compared in the experiment.

	Reference signal	Control method	Controller output constraints
Conventional 1	r^*	PID control	Not exist
Conventional 2	r^*	PID control with anti-windup [19]	Exist
Proposed 1	$r_{\rm opt}$	PID control	Not exist
Proposed 2	$\hat{r}(\alpha_k)$	PID control	Exist

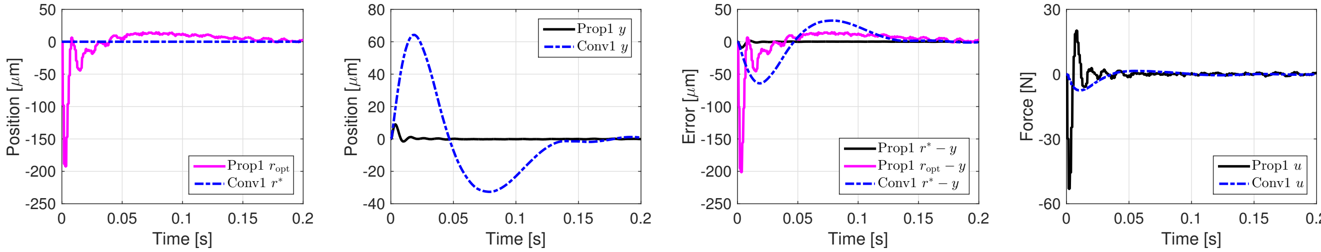


(a) Structure of the experimental stage. (b) Frequency response of the experimental stage.

Fig. 6. Experimental stage.

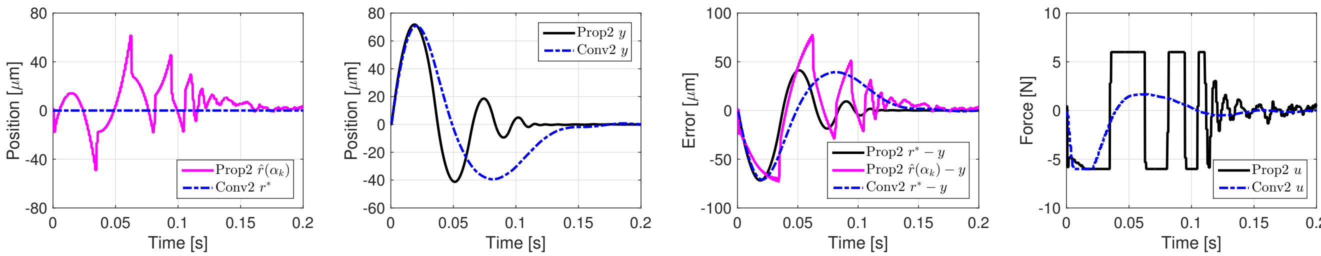
V. Conclusion

This paper shows that the impulse input disturbance response is improved by modifying the reference signals properly. Next, we propose the disturbance suppression control based on RG considering the controller output constraint. Finally, the effectiveness of the proposed methods is demonstrated by experiments. This paper focuses on the disturbance suppression performance that has not been discussed in the previous studies of RG and makes it possible to modify the reference signal in response to the disturbance. Unexpected



(a) Reference command. (b) Plant output. (c) Position error. (d) Controller output.

Fig. 7. Experimental results of disturbance suppression control by reference command modification based on MPC.



(a) Reference command. (b) Plant output. (c) Position error. (d) Controller output.

Fig. 8. Experimental results of disturbance suppression control by reference command modification based on RG.

disturbances with large amplitudes can be suppressed by an extension of the proposed method. The verification of the robustness to modeling errors and of the relationship between the magnitude of disturbance and the number of steps κ to generate MAS will be discussed in future works.

References

[1] H. Butler, "Position Control in Lithographic Equipment [Applications of Control]," *IEEE Control Systems*, vol. 31, pp. 28–47, oct 2011.

[2] Y. M. Choi and D. G. Gweon, "A High-Precision Dual-Servo Stage Using Halbach Linear Active Magnetic Bearings," *IEEE/ASME Transactions on Mechatronics*, vol. 16, pp. 925–931, oct 2011.

[3] R. van Herpen, T. Oomen, E. Kikken, M. van de Wal, W. Aangenent, and M. Steinbuch, "Exploiting additional actuators and sensors for nano-positioning robust motion control," *Mechatronics*, vol. 24, pp. 619–631, sep 2014.

[4] Y. Yazaki, H. Fujimoto, Y. Hori, K. Sakata, A. Hara, and K. Saiki, "Method to Shorten Settling Time Using Final State Control for High-Precision Stage with Decouplable Structure of Fine and Coarse Parts," *IEEJ Transactions on Industry Applications*, vol. 135, no. 3, pp. 227–236, 2015.

[5] H. Fujimoto, Y. Hori, and A. Kawamura, "Perfect tracking control based on multirate feedforward control with generalized sampling periods," *IEEE Transactions on Industrial Electronics*, vol. 48, pp. 636–644, jun 2001.

[6] Y. Yazaki, H. Fujimoto, K. Sakata, A. Hara, and K. Saiki, "Application of mode switching control using initial state variables in constraint final-state control to high-precision dual stage," in *2015 American Control Conference (ACC)*, pp. 4155–4161, IEEE, jul 2015.

[7] T. Oomen, R. van Herpen, S. Quist, M. van de Wal, O. Bosgra, and M. Steinbuch, "Connecting System Identification and Robust Control for Next-Generation Motion Control of a Wafer Stage," *IEEE Transactions on Control Systems Technology*, vol. 22, pp. 102–118, jan 2014.

[8] E. Gilbert, I. Kolmanovsky, and K. T. Tan, "Nonlinear control of discrete-time linear systems with state and control constraints: a reference governor with global convergence properties," *Proceedings of 1994 33rd IEEE Conference on Decision and Control*, vol. 1, pp. 144–149, 1994.

[9] Y. Ohta and I. Masubuchi, "On the implementation of reference governor," in *Proc. 40th Annual Conference of IEEE Industrial Electronics Society (IECON 2014)*, pp. 215–220, 2014.

[10] A. Bemporad, A. Casavola, and E. Mosca, "Nonlinear control of constrained linear systems via predictive reference management," *IEEE Transactions on Automatic Control*, vol. 42, no. 3, pp. 340–349, 1997.

[11] A. Casavola, E. Mosca, and M. Papini, "Control Under Constraints: An Application of the Command Governor Approach to an Inverted Pendulum," *IEEE Transactions on Control Systems Technology*, vol. 12, no. 1, pp. 193–204, 2004.

[12] E. G. Gilbert and C. J. Ong, "Constrained linear systems with hard constraints and disturbances: An extended command governor with large domain of attraction," *Automatica*, vol. 47, no. 2, pp. 334–340, 2011.

[13] M. J. Dillsaver, U. V. Kalabic, I. V. Kolmanovsky, and C. E. S. Cesnik, "Constrained control of very flexible aircraft using reference and extended command governors," in *2013 American Control Conference*, pp. 1608–1613, IEEE, jun 2013.

[14] S. Aghaei, F. Sheikholeslam, M. Farina, and R. Scattolini, "An MPC-based reference governor approach for offset-free control of constrained linear systems," *International Journal of Control*, vol. 86, no. 9, pp. 1534–1539, 2013.

[15] T. Hatanaka and K. Takaba, "Design of Reference Governor for Constrained Systems Subject to Disturbance," *Transactions of the Society of Instrument and Control Engineers*, vol. 40, no. 8, pp. 806–814, 2004.

[16] G. Goodwin, S. Graebe, and M. Salgado, *Control System Design*. Prentice-Hall, 2001.

[17] E. G. Gilbert and K. T. Tan, "Linear systems with state and control constraints: The theory and application of maximal output admissible sets," *IEEE Transactions on Automatic Control*, vol. 36, no. 9, pp. 1008–1020, 1991.

[18] K. Hirata and K. Kogiso, "An Off-Line Reference Management Technique for Constraint Fulfillment," *Transactions of the Institute of Systems, Control and Information Engineers*, vol. 14, no. 11, pp. 554–559, 2001.

[19] K. Ohishi and T. Mashimo, "Design Method of Digital Robust Speed Servo System Considering Output Saturation," *IEEJ Transactions on Industry Applications*, vol. 119, no. 1, pp. 88–96, 1999.