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RESEARCH ARTICLE / ARAŞTIRMA MAKALESİ

Stabilization and DOB-Based Disturbance Rejection for MBT Gun-Barrel Elevation Drive

Savaş Tankı Namlu Yükseliş Açısı Tahrik Sistemi Stabilizasyonu ve DOB-Temelli Bozucu Dışlama

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Abstract
Control systems for main battle tanks become more important while the vehicles become more complex. Mobile vehicles in battlefield lead to the requirement of firing during the motion instead of pausing each time the main battle tank engages a target. This demand can be achieved by weapon control system that minimize the tank hull movement effects on the barrel. Systems designed for this stabilization task are basically closed loop servo systems that control the angular position of the barrel by using feedback signals produced by a rate gyroscope mounted on the barrel (breech) to measure its angular velocity. Second-generation control systems contain an extra gyro which feeds the tanks movement forward in the system to make the turret more sensitive and rapid against the disturbance due to tanks movement. In this paper we use a disturbance observer that do not require measurements of muzzle angular velocity and rough terrain caused disturbance due to tank movement. Designed observer eliminate the requirement for measurements of near-perfect feedforward signal.
Keywords: Gun-barrel stabilization, dynamic modeling, linear control, disturbance observer, battlefield simulation.

Öz
Savaş tanklarındaki son yıllardaki gelişmeler kullanılan kontrol sistemlerini daha önemli hale getirmiştir. Bu araçların savaş alanında hareket halinde olması, bir hedefe ateş etme sırasında durmak yerine hareket esnasında ateş etmelerini gerekli kılmaktadır. Bu gereklilik, tank gövdesi hareketlerinin namluya olan etkisini minimize eden silah kontrol sistemi ile sağlanabilir. Bu stabilizasyon işlevi için namlu üzerine monte edilen jiroskoptan alınan açısal konumun geri beslemesiyle çalışan kapalı-evrim servo kontrol sistemleri kullanılır. İkinci nesil kontrol sistemlerinde, tank gövdesinin hareketi nedeniyle oluşan bozucu etkilere karşıtareti daha hassas ve hızlı kılan, ileri beslemeli kontrol için ekstra bir jiroskop daha kullanılır. Bu makalede ise tankın hareketi nedeniyle oluşan bozucu etkilerin ölçülmesi ihtiyacını ortadan tamamen kaldıran bir 'bozucu etki gözleyicisi' kullanılmaktadır. Tasarlanan gözleyici sayesinde bozucu etkinin hatasız olarak ölçülmesi ve ileri besleme kontrol ile elimine edilmeye çalışılması gerekliliği ortadan kalkmaktadır.
Anahtar Kelimeler: Dinamik modelleme, doğrusal kontrol, bozucu etki gözleyicisi, savaş alanı simülasyonu, namlu stabilizasyonu

I. INTRODUCTION

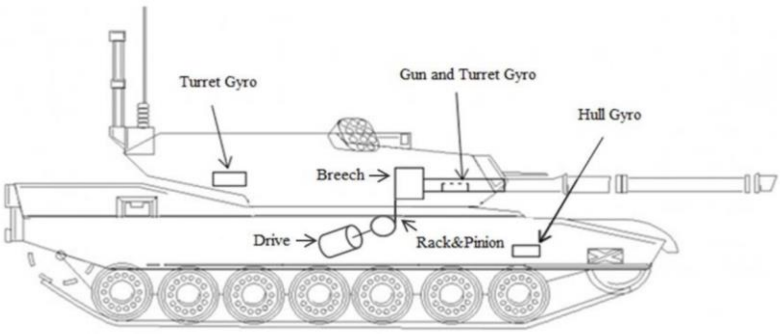

Figure 1: MBT and gyro locations

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Modern armored land vehicles have crucial importance on todays battlefield. However, due to their large size and relatively low speed, they can often be an obvious target while traversing rugged, harsh terrain. Their ability to locate a target accurately and stabilizing the gun-barrel during the shot while moving out of the line-of-sight can make all the difference. Main Battle Tank (MBT) is probably the most important weapon in battle_eld due to its mobility and heavy-fire capacity. Developments on MBT follow the improvements in design of heavy weaponry, Weapon Control Systems (WCS) and enhanced mobility. WCS have become more crucial while the MBT have evolved into larger and more complex systems. Mobile vehicles in battlefield lead to the requirement of firing during the motion instead of pausing each time the main battle tank engages a target. This demand can be achieved by weapon control system that minimize the tank hull movement effects on the barrel. It is expected that gunners minimize this disturbance by manually rotating the barrel in the opposite direction of the hull motion. But although the frequency of this motion ranges from 0 to 4 Hz, the response of the human operators is limited to a maximum 0.5 Hz [1]. Therefore, the effects of disturbance on the barrel can only be minimized by automatic control systems which are designed to stabilize the barrel position during the vehicle motion.

Systems designed for this stabilization task are basically closed loop servo systems that control the angular position of the barrel by using feedback signals produced by a rate gyroscope mounted on the barrel (breech) to measure its angular velocity. Feedback control systems are proved to be somewhat effective, but rapidly correcting the stabilization errors during tank motion on a rough terrain to a sufficiently low level was not easy for the operators. This problem led to the “second-generation" control systems in early sixties. These systems contain an extra gyro which feeds the tanks movement forward in the system to make the turret more sensitive and rapid against the tanks movement (Figure 1). Usually hull feedforward gyro measures the disturbance acting on yaw motion and the turret feedforward gyro measures the disturbance on pitch motion of the tank. This method lowers the stabilization error by 50 % of the error in basic systems [1].

In [2] control performance for balanced and out of balanced turret-barrel structures are compared using a 2-dof barrel model. Feedback control is complemented with feedforward control in [3] using field measured disturbance data. In [4] elevation and azimuth dynamics of MBT is derived including a half-vehicle suspension system model. PID, LQR and back-stepping control is used and compared in [5] using a 2-dof barrel model incorporated with suspension system dynamics. Continuous exible and rigid models of barrel and the drive line are investigated and compared in [6]. Model predictive control is used in [7] to handle the constraints in barrel motion. In [8] active disturbance rejection control method is used incorporating nonlinear disturbance model and the performance is compared with respect to PID control.

Control applications often assume availability of near-perfect feedback (and/or feedforward) signals. However, such an assumption is often invalid. Firstly, sensors are expensive and they can substantially raise the total cost of a control system. Second, sensors and their associated wiring reduce the reliability of control systems. Third, some signals are impractical to measure. Fourth, sensors usually induce significant errors such as stochastic noise, cyclical errors, and limited responsiveness. Hence, in this paper, we have used a disturbance observer (DOB) to eliminate the hull gyro for disturbance measurement. Using a DOB, we have eliminated the disturbance acting on the system up to the bandwidth of the observer's low pass filter [9]. Moreover, DOB also provides robustness with respect to modeling errors [10].

The paper is organized as follows: In Section 2 we derive the dynamic model of the elevation control system. In Section 3 we present the concept of observer based control. In Section 4 we show the numerical simulation results of the closed-loop feedback control system using a DOB in the inner loop and PI controller in the outer loop. In Section 5 we present our final comments.

II. SYSTEM MODEL

Model of the elevation system consists of the drive line and the gun barrel is shown in Figure 2. Model is based on lumped parameter beam formulation. The gun-barrel is divided into two parts, muzzle and breech sections, which somewhat provides means to analyze flexible behavior of the barrel. The elevation drive consists of an electric motor, providing the required torque to rotate gun-barrel in vertical plane about the trunnion support. Model consists of the rotational degrees of freedom θ_d, θ_1 and θ_2 for the drive, breech and muzzle sections, respectively, with respect to their center of gravity (CG) locations. Tank hull may get inclined during its motion on a rough terrain with a pitch angle θ_p relative to the horizontal axis. Model also incorporates vertical translational degrees of freedom x_1 and x_2 for the breech and muzzle sections, respectively, measured relative to their CG locations. Elevation motor drives a pinion, which transforms the torque generated to breech section using rack and pinion mechanism. Torsional damping imposed by the hinge joint of the trunnion is considered to be linear viscous damping in the model. The connection of breech and muzzle sections is modeled to be a hinge joint, with linear torsional sti_ness and linear torsional viscous damping characteristics. The trunnion may also have a vertical displacement y_t during tanks motion on the field.

Rotational dynamics of the drive system, and breech and muzzle sections are:

$$I_d\ddot{\theta}_d + c_d\dot{\theta}_d + k_d(\theta_d R_p + (\theta_p - \theta_1)X_{tp})R_p = K_t v_i, \tag{1a}$$

$$I_1\ddot{\theta}_1 + c_{1p}(\dot{\theta}_1 - \dot{\theta}_p) + f_t\eta_1 - c_{12}(\dot{\theta}_2 - \dot{\theta}_1) - k_{12}(\theta_2 - \theta_1) - k_d(\theta_d R_p + (\theta_p - \theta_1)X_{tp})(X_{tp} + \eta_1) + f_{12}(l_1 - \eta_1) = 0, \tag{1b}$$

$$I_2\ddot{\theta}_2 + c_{12}(\dot{\theta}_2 - \dot{\theta}_1) + k_{12}(\theta_2 - \theta_1) + f_{12}\eta_2 = 0. \tag{1c}$$

Translational equations of motion for the breech and muzzle sections of the barrel are:

$$m_1\ddot{x}_1 - f_t + k_d(\theta_d R_p + (\theta_p - \theta_1)X_{tp}) + f_{12} = 0, \tag{2a}$$

$$m_2\ddot{x}_2 - f_{12} = 0. \tag{2b}$$

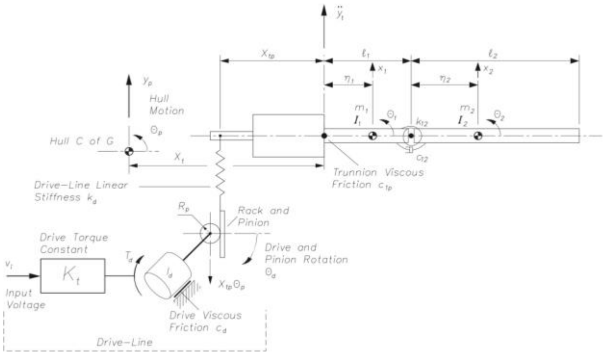


Figure 2: Elevation drive model [2]

In the set of equations (1) and (2), f_t and f_{12} are the reaction forces applied by the trunnion to the breech and by the breech to the muzzle sections respectively. Furthermore, we have geometric constraints for the elevation dynamics to read

$$x_1 = y_t + \theta_1\eta_1, \text{ and } x_2 = y_t + \theta_1 l_1 + \theta_2\eta_2.$$

Using the geometric constraints to eliminate the translational equations of motion and substituting the equations (2) into equations (1) to also eliminate the constraint forces, one can obtain the system dynamics in multivariable matrix form

$$M\ddot{\boldsymbol{\theta}} + D\dot{\boldsymbol{\theta}} + K\boldsymbol{\theta} = F\mathbf{u}, \tag{3}$$

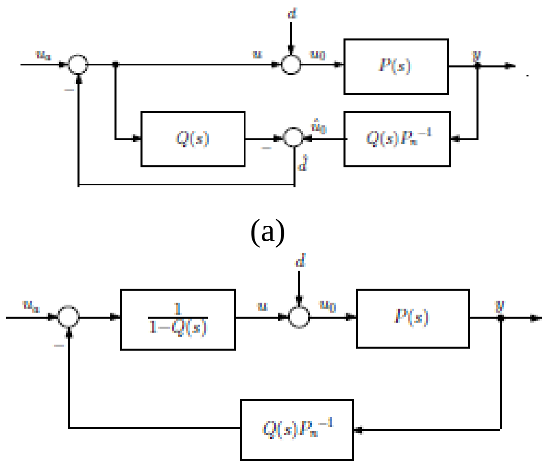
where $\boldsymbol{\theta} := (\boldsymbol{\theta_d \theta_1 \theta_2})^T$ and $\boldsymbol{u} := (\boldsymbol{v_i \ddot{y}_t \dot{\theta}_p \theta_p})^T$. Matrices M, D, K, F in (3) are

$$M = \begin{pmatrix} I_d & 0 & 0 \\ 0 & I_1 m_1\eta_1^2 + m_2 l_1^2 & m_2 l_1 \eta_2 \\ 0 & m_2 l_1 \eta_2 & I_2 + m_2\eta_2^2 \end{pmatrix}, \quad D = \begin{pmatrix} c_d & 0 & 0 \\ 0 & c_{1p} + c_{12} & -c_{12} \\ 0 & -c_{12} & c_{12} \end{pmatrix},$$

$$K = \begin{pmatrix} k_d R_p^2 & -k_d R_p X_{tp} & 0 \\ -k_d X_{tp} R_p & k_{12} + k_d X_{tp}^2 & -k_{12} \\ 0 & -k_{12} & k_{12} \end{pmatrix}, \quad F = \begin{pmatrix} K_t & 0 & 0 & -k_d X_{tp} R_p \\ 0 & -(m_1\eta_1 + m_2 l_1) & c_{1p} & k_d X_{tp}^2 \\ 0 & -m_2\eta_2 & 0 & 0 \end{pmatrix}.$$

Finally, system dynamics can be represented by the state-space equations

$$\dot{\boldsymbol{\xi}} = A\boldsymbol{\xi} + B\mathbf{u} \quad \text{and} \quad \mathbf{y} = C\boldsymbol{\xi} \tag{4}$$



(a)

(b)

Figure 3: Equivalent block diagrams for DOB-based disturbance rejection

with the states $\boldsymbol{\xi} = (\boldsymbol{\theta_d \theta_1 \theta_2 \dot{\theta}_d \dot{\theta}_1 \dot{\theta}_2})^T$ and with the system and input matrices

$$A = \begin{pmatrix} 0 & I \\ -M^{-1}K & -M^{-1}D \end{pmatrix}, \quad B = \begin{pmatrix} 0 \\ M^{-1}F \end{pmatrix}.$$

Matrix C depends on the output(s) of interest or on the measurement(s) available.

III. DOB-BASED CONTROLLER DESIGN

Disturbance observer (DOB) is an e_ective method to achieve robustness against disturbances and model uncertainties. DOB provides an estimate $\hat{d}$ of the disturbance d, which is used to perform a compensation using a negative feedback loop. The DOB is used only for disturbance rejection; an additional outer control loop, as shown in Figure 2, is still required to achieve the desired control performances. Figure 3 shows two equivalent block diagrams of the DOB system. A low-pass _lter Q(s) is necessary because the inverse $P_n^{-1}(s)$ of the nominal plant model $P_n(s)$ is usually not a proper transfer function. Analysis of DOB feedback loop leads to the transfer functions

$$G_{u_a y}(s) := \frac{Y(s)}{U_a(s)} = \frac{P(s)P_n(s)}{Q(s)[P(s) - P_n(s)] + P_n(s)}$$

$$G_{dy}(s) := \frac{Y(s)}{D(s)} = \frac{P(s)P_n(s)[1 - Q(s)]}{Q(s)[P(s) - P_n(s)] + P_n(s)}$$

revealing that if the nominal plant is correct (i.e., $P_n(s) = P(s)$), $G_{uay}(s) = P(s)$, and $G_{dy}(s) = P(s)[1-Q(s)]$. The condition $G_{uay}(s) = P(s)$ implies that the DOB is "transparent" to the outer loop controller, i.e., it does not a_ect the dynamics from u_a to y. Hence, as long as the nominal model is correct, the DOB and the outer controller can be designed independently. The DOB design is essentially a matter of selecting the low-pass filter Q(s). A commonly used structure is [9]

$$Q(s) = \frac{1 + \sum_{k=1}^{N-r} a_k(\tau s)^k}{1 + \sum_{k=1}^{N} a_k(\tau s)^k} \tag{5}$$

where N, r, and $\omega_c = 1/\tau$ are the order, relative degree, and cut-off frequency of Q(s) respectively. The coefficients α_k of the denominator are usually chosen as the coefficients of Butterworth or binomial polynomial.

Regarding the modeling errors end uncertainties (i.e., $P_n(s) \neq P(s)$), note that $Q(s) \approx 0$ at high frequencies, and

$$G_{u_a y}(s) \approx \frac{P(s)P_n(s)}{P_n(s)} = P(s), \quad G_{dy}(s) \approx \frac{P(s)P_n(s)}{P_n(s)} = P(s).$$

Hence DOB loop behaves like the real plant. However, at low frequencies where $Q(s) \approx 1$,

$$G_{u_a y}(s) \approx \frac{P(s)P_n(s)}{P(s)} = P_n(s), \text{ and } G_{dy}(s) \approx 0.$$

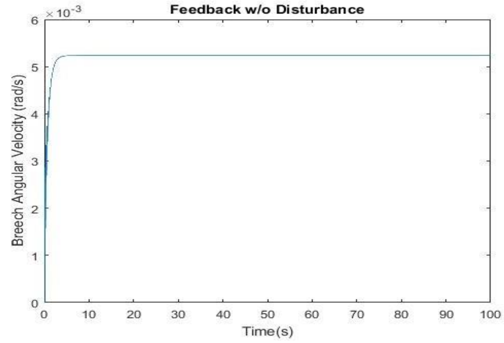


Figure 4: Breech angular position tracking reference 0.3 deg/s input

Therefore, at sufficiently low frequencies, DOB loop nominalizes the dynamics of the plant to be controlled and eliminates the effect of disturbance.

IV. NUMERICAL SIMULATIONS AND RESULTS

In this section we design state and disturbance observers and we synthesize feedback PID controllers for a MBT gun-barrel system. Performance of observer based controllers are established and compared with standard controllers.

4.1. System Data

Numerical data for the MBT gun-barrel is given in Table 1, which is adapted from [4].

Table 1: MBT Gun-Barrel Data

Symbol	Value	Unit	Symbol	Value	Unit	Symbol	Value	Unit
X_t	1.00	m	c_{1p}	1.50	kNms/rad	c_{12}	2.00	kNms/rad
X_{tp}	0.75	m	m_1	2.17	Mg	m_2	335	kg
k_d	6.00	MNm/rad	I_1	1.09	Mgm^2	I_2	0.31	kgm^2
c_d	1.50	kNms/rad	l_1	1.75	m	l_2	281	kgm^2
R_p	0.04	m	η_1	0.47	m	η_2	1.32	m
I_d	0.50	kgm^2	k_{12}	4.00	MNm/rad	K_t	15.0	kNm/V

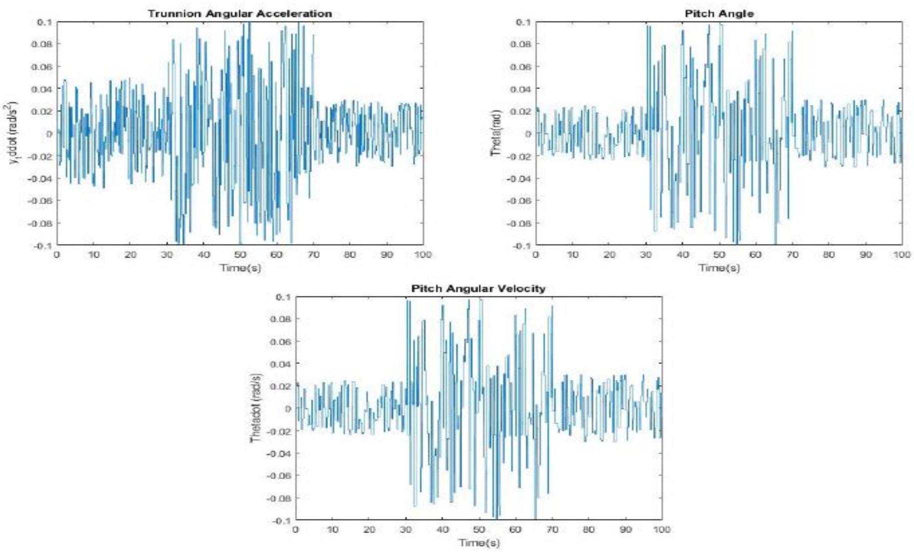


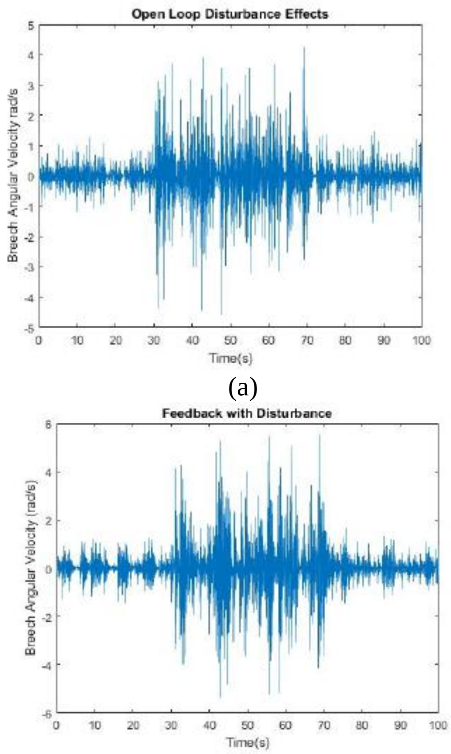
Figure 5: Field measured disturbances during motion

4.2. Controller Design and Simulations in Stand Still

Main controller in outer-loop feedback (Figure 3) can be designed by root locus method to track a step reference of 0.3 deg/s. Using a PI controller, gains are found to be K_p=1, K_i = 5.26. Angular velocity of the breech without disturbance effects is shown in Figure 5. We desire to elevate the muzzle to 30 degrees but due to 2.5 sec settling time delay, we have 0.17 degrees (0.3 mrad) error in the angular position. However, this is below the accepted tolerance which is 0.5 mrad [1].

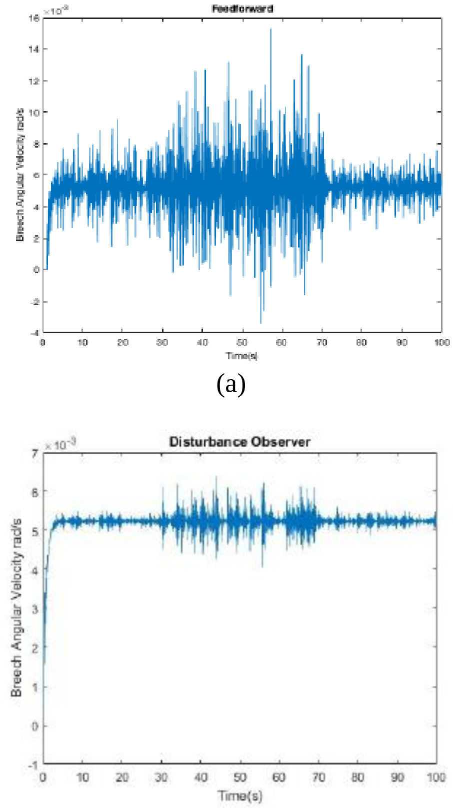
4.3. Controller Design and Simulations During Motion

Field measured disturbances on MBT during motion [3] are shown in Figure 6. Disturbances are injected to the plant (MBT) and the simulated breech angular velocity in open loop and closed-loop with the PI feedback controller at constant barrel angular position are shown in Figure 7. It is clear from the plots that basic feedback control has no effect on eliminating the effect of rough terrain disturbance. It is well known that feedforward (FF) control based on disturbance measurement to complement the feedback control system can provide better performance on disturbance rejection problems. This method is used in Type 2 MBT control systems [1] and it has been implemented successfully in weapon control technology and in related research such as [3]. However, it requires an additional gyro to measure terrain disturbance. To eliminate this additional sensor requirement



(b)

Figure 6. Effect of disturbance on breech angular velocity



(b)

Figure 7. Disturbance rejection performance with FF versus DOB control

we have designed a DOB controller as shown in Figure 4. Transfer function of DOB controller's low pass filter in accordance with equation (6) is $Q(s) = 1/(s^3+3s^2+3s+1)$. Disturbance rejection performance of the control system using feedforward control (incorporating the same LP filter) versus DOB integrated control with 0.3 deg/s step breech velocity input is shown in Figure 8. It is clear that DOB based control system outperforms FF control in this problem.

V. CONCLUSIONS

In this paper we have studied the dynamics and observer based stabilization of a main battle tank elevation system. We have derived the dynamics of the elevation drive incorporating 2-dof to reflect the flexibility of the gun-barrel. We have used a disturbance observer to eliminate the effects of disturbance on a rough terrain instead of the commonly used feedforward control with gyro measurement. Simulation results are presented to show the stabilization performance of the system with the synthesized controllers. We observed that PI feedback controller provides sufficient performance in stand still for precise gun orientation towards the target. However, when MBT moves on a rough terrain basic feedback control cannot attenuate the disturbance. We have incorporated a DOB to feedback control to eliminate the effect of disturbance and we have compared its performance with the system using FF control. It is evident that DOB based control system outperforms the system with FF control in this problem.

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