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ANALYSIS OF A DC MOTOR BASED VELOCITY CONTROLLER USING DISTURBANCE OBSERVER

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ABSTRACT

Motion control incorporates a range of challenges when it comes to the control of mechanical systems. In rotary motion; position, velocity and acceleration control are the tasks required most often for robotics. The achievement of velocity control is one of the popular technical issues in motion control and industrial applications. The traditional approach for velocity control is PID based feedback controllers. PID controllers are not suitable for the applications subjected to higher external disturbances. This paper proposes a Disturbance Observer (DOB) based velocity controller. DOB together with the tuned PID controller can make the system robust. To validate the proposed method, stability analysis and experiments were carried out with and without DOB. The velocity responses of the experiments were analyzed for different modes of disturbances with different observer gains. The performance of the proposed controller shows enhanced results compared to the traditional velocity controllers.

KEYWORDS : Disturbance Observer, Motion Control, Observer Gain, PID Controller, Stability Analysis, Velocity Controller

Motion control includes a wide range of issues related to the control of mechanical systems. In robotics applications, DC motors have been widely used due to their simple structure, outstanding control performance and low cost. In this paper, the authors focus on controlling the speed (velocity control) of a DC servo motor. The DC motor is the simplest machine which converts electrical energy to the mechanical energy. Electrical equivalent model of a DC motor is shown in figure. 1.

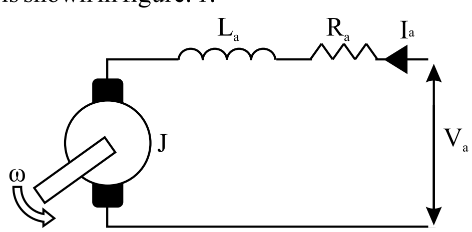

Figure 1: Electrical model of a DC motor

Most of the velocity controllers are open loop. For the closed loop control systems, one of the very popular methods of controlling the velocity is feedback based PID controllers. PID based controllers perform satisfactorily for insignificant external disturbances. In order the velocity controller to perform effectively, the system has to withstand in any varying environment. The robustness of motion systems is essential to attain such high performance as needed for the velocity controller (Ohnishi et al; 1994).

In this paper, the authors have proposed the disturbance observer to use in a closed loop velocity control system to compensate the disturbances (Hasala et al; 2012). By introducing the DOB, the accuracy of the response as well as the system robustness are expected to be enhanced. DOB identifies the total mechanical load and the effect of system parameters change which considers as the total disturbance of the motor (Katsuhiko; 2006).

The objective of this research is to analyze the performance of a DC servo motor with and without disturbance observer and to validate the system performance theoretically as well as practically. Stability of the system is analyzed theoretically and experimentally verified. Stability analysis was carried out to check the sensitivity of the system for specific parameter changes (disturbances).

The experiment was conducted for three types of disturbances; supporting disturbance, opposing disturbance and periodic disturbance, for different observer gains. The external disturbances were produced by another DC motor with different ratings, coupled to the main motor.

The paper is organized as follows. In the following section, the modeling of PID based velocity controller is presented. In this section, PID based velocity controller with DOB is mathematically derived. In results and discussion section, the stability of the velocity controller with and without DOB is analyzed. The experiment carried out with different observer gains and external disturbances was also discussed in this section. Finally, the paper is summarized under conlusion.

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MATERIALS AND METHODS

1. PID based velocity controller

Figure 2 shows the PID based velocity controller. Velocity can be controlled using the voltage (Kuo; 2003). According to (1) the motor torque can be controlled by controlling the armature current.

$$T_m(s) = K_t I_a(s) \tag{1}$$

Where T_m is motor torque, K_t is the torque constant and I_a is the armature current. Back emf also plays an important role as a feedback in this controller (Guoshing and Shuocheng; 2008).

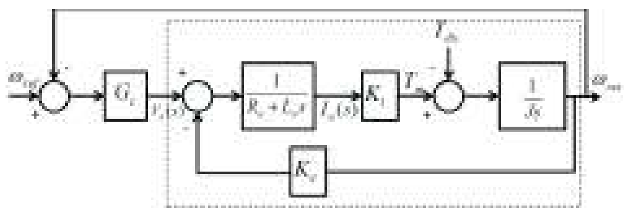

Figure 2 : PID based velocity controller

Where, ω_{ref} is reference velocity, ω_{res} is velocity response, G_c is the transfer function of PID controller, V_a is armature voltage, R_a is armature resistance, L_a armature inductance, T_{dis} is total disturbances, J is motor inertia and K_e is back emf constant.

$$G_c = K_p + \frac{K_i}{s} + K_d s \tag{2}$$

Transfer function of figure 2 is given by (3).

$$\omega_{res} = \frac{[(\omega_{ref} - \omega_{res})G_c - K_e\omega_{res}]}{R_a + L_a s}(K_t - T_{dis})(\frac{1}{Js}) \tag{3}$$

In order to analyze the system stability of figure 2. the transfer functions were derived with and without disturbances (T_{dis}).

Case 1: without disturbances (T_{dis} =0)

$$G_1(s) = \frac{G_c K_t}{(R_a + L_a s + Js) + K_t(G_c + K_e)} \tag{4}$$

Where, $G1(s) = \omega_{res} / \omega_{ref}$

Case 2: with disturbances (ω_{ref} =0)

$$S_1(s) = \frac{-(R_s + L_a s)}{(R_a + L_a s + Js) + K_t(G_c + K_e)} \tag{5}$$

Where, $S1(s) = \omega_{res} / T_{dis}$

Stability analysis for above two cases is discussed in the results..

2. Disturbance Observer (DOB)

DC motors are frequently subjected to different types of unknown disturbances such as external loads. These disturbances affect the performance of DC motor and may cause the system unstable. Controlling DC motor with unknown disturbances is a challenging task. DOB is used to suppress the unknown disturbances from the system. This estimation may then be used to compensate for the disturbance torque acting on the shaft thus, improving the system robustness to external toques and the load changes. The magnitude of the disturbance can be estimated and then be used to improve the performance of the control systems (Mizuochi et al., : 2006).

The disturbance torque can be obtained from (6). Here, K_t is the motor constant, J is the inertia of the load coupled to the rotor and the subscript n is used to denote the nominal values.

$$T_{dis} = K_{tn} I_a^{ref} - J_n \ddot{\theta} \tag{6}$$

Control block diagram of above equation is shown in figure 3.

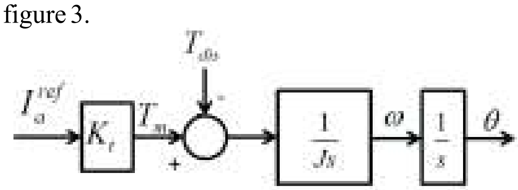

Figure 3: Block diagram of the motor with disturbance

The disturbance torque (T_{dis}) can be calculated from angular acceleration of the motor and the current reference. In practical situations, the angular acceleration cannot be measured directly using available sensors. Therefore, it is normally calculated by differentiating the angular displacement measured from the wheel encoders.

As shown in figure 4, T_{dis} represents the sum of external load torque, fixed friction and viscous friction. Where, is the estimated disturbance torque. Furthermore, a low pass filter is used at the output of the disturbance torque calculation to cancel out the noise components of the differentiator. If the filter is of the first order, the output can be expressed as,

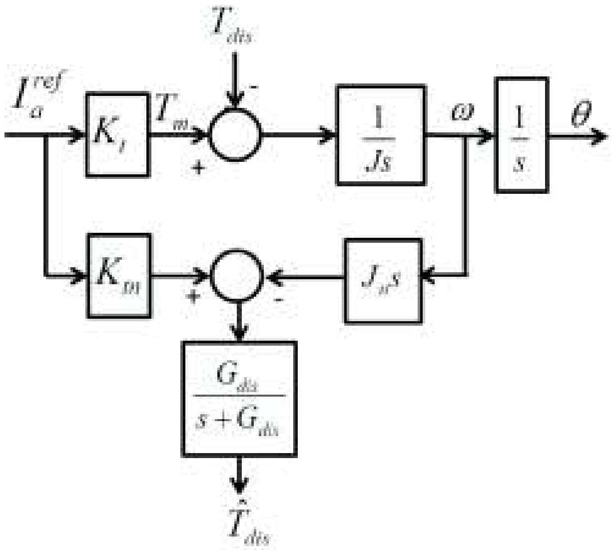

Figure 4: Control block diagram of disturbance observer

$$\hat{T}_{dis} = \frac{G_{dis}}{(s+G_{dis})}(K_{tn} I_a - J_n \ddot{\theta}) \qquad (7)$$

System represented by figure 4. Is derrived after introducing the pseudo derivative (Nwokah and Osita, 1987) and a low pass filter which would improve the performance significantly. Where, G_{dis} is the angular cutoff frequency of the low pass filter. The disturbance observer estimates the disturbance torque on the control system and compensates for it (Abeykoon et al., 2008).

3. PID based velocity controller with DOB

Motor disturbance includes the frictional effects, load and the effects of parameter variations (Abeykoon, 2008). Usually this disturbance is not measurable. However, if a control block as shown in figure 4., is implemented, the motor disturbance (T_{dis}) will become measurable and it is usually taken out after a low pass filter as indicated in the same figure.

Disturbance observer observes the disturbance force in the system without using force sensors. It is designed to estimate the disturbance with the help of a encoder and a current sensor attached to the motor (Katsura et al., 2008). Figure 5 shows the PID based velocity controller with disturbance observer. This was the control system which used at the experiment to validate the proposed controller.

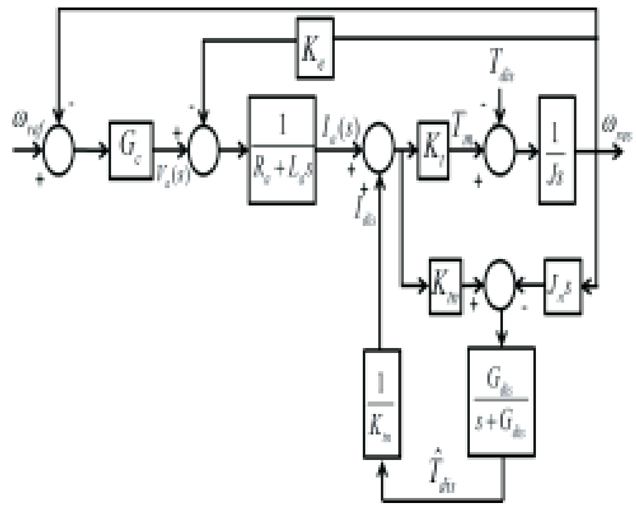

Figure 5: PID based velocity controller with DOB

Similarly, as done under PID based velocity controller above, another two transfer functions were derived for the system when DOB is present.

Case 1: without disturbances (T_{dis} =0)

$$G_2(s) = \frac{[K_t K_{tn} G_c (s+G_{dis})]}{[s(R_a + L_a s)(J_n K_{tn} s + J_n K_t G_{dis}) + K_t K_{tn}(s+G_{dis})(K_e + G_e)]} \qquad (8)$$

Where, G2(s) = $\omega_{res}/\omega_{ref}$

Case 2: with disturbances (ω_{ref} =0)

$$S_2(s) = \frac{[K_{tn} G_{dis}(R_a + L_a s) - (K_{tn}(R_a + L_a s)(s+G_{dis}))]}{[K_{tn} Js(R_a + L_a s)(s+G_{dis}) - K_{tn} K_t (G_c + K_e)(s+G_{dis}) - sG_{dis}(J_n K_t + K_{tn} J)(R_a + L_a s)]} \qquad (9)$$

Where, S2(s) = ω_{res}/T_{dis}

However the effect of the low pass filter and friction component B has been neglected in the analysis.

RESULTS AND DISCUSSION

1. Stability analysis

In the stability analysis of the system, the torque

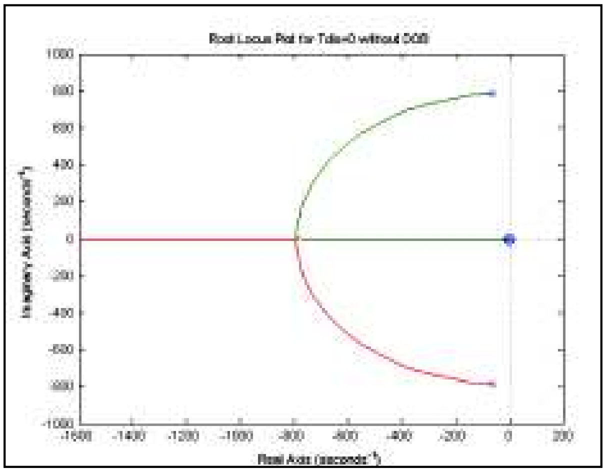

Figure 6 : Root locus plot for T_{dis}=0, without DOB

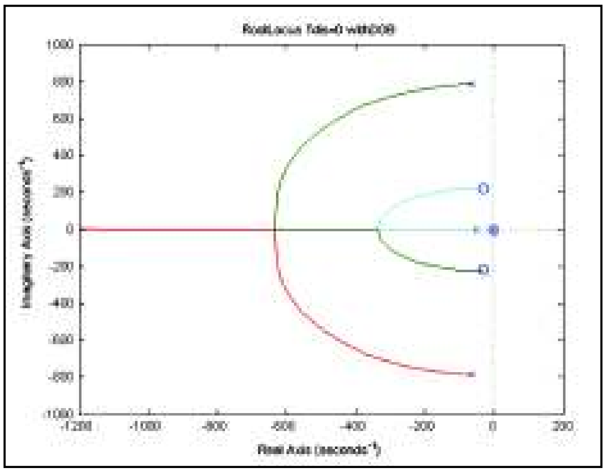

Figure 7 : Root locus plot for T_{dis}=0, with DOB

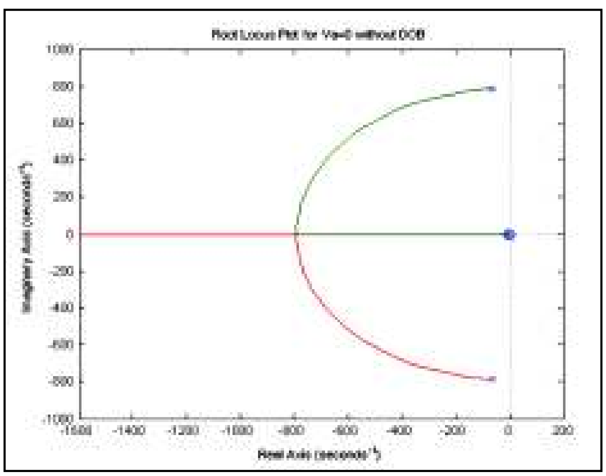

Figure 8 : Root locus plot for ω_{ref} =0, without DOB

coefficient and inertia were considered as non-varying and equal to their nominal values. For the simplicity of the calculations, a one DOF system was considered.

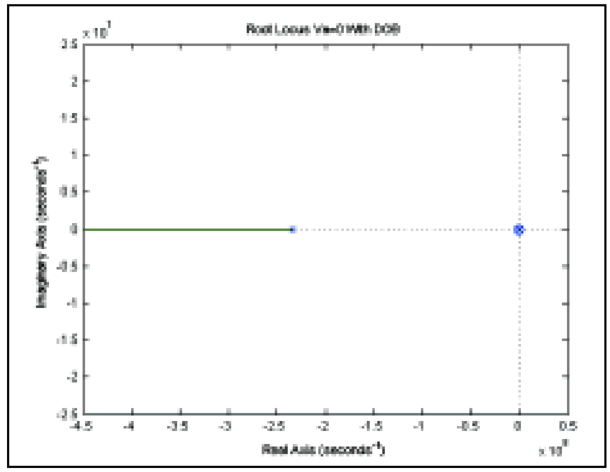

Figure 9 : Root locus plot for ω_{ref} =0, with DOB

Figure 6 and 8 show the root locus plot for the open loop transfer functions of (4) and (5) respectively without applying DOB. Both loci have the same shapes since the denominators of (4) and (5) are similar. According the loci, the PID based system is stable. Once DOB is introduced, both systems' (T_{dis}=0 and ω_{ref}=0) stability improves. These improvements are evident from the pole movements of root loci in figure 7 and 9.

2. Experimental results

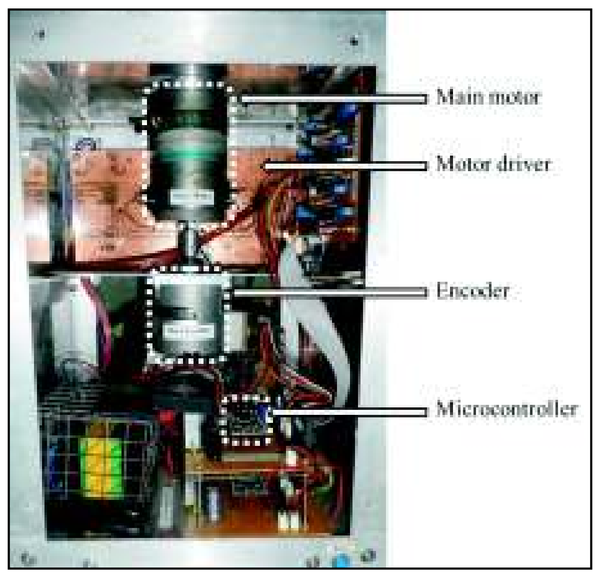

Figure 10: Experimental setup

Figure 10 shows the hardware arrangement of the experimental platform. The main motor is by Electrocraft Inc with the specifications listed in table 2. The hardware platform consists of a PWM driven motor driver with a driver IC (DRV8432 by Texas Instrument) which can carry current up to 14A with 24A peak load. The motor driver is operated by the PWM signals generated from mbed NXPLPC1768 microcontroller. Position sensing is done by an encoder coupled to the main motor.

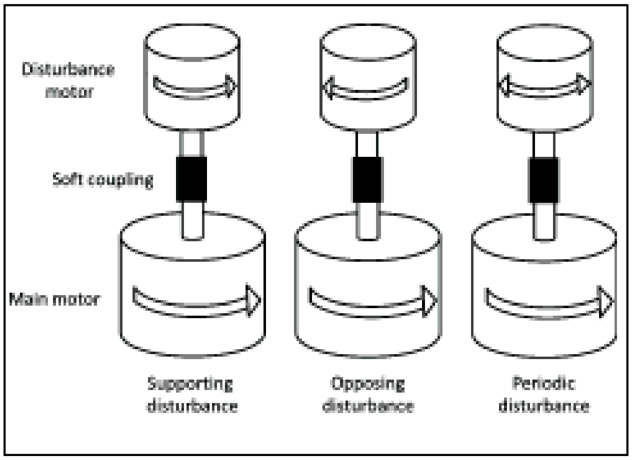

Figure 11: Different modes of disturbances

As shown in figure 11, the external disturbances were applied using an another small DC motor with different ratings. The motor shafts were coupled and the disturbance motor was mounted on top of the main motor to minimize the gravity effect of the coupled motor. The disturbances were applied in three modes; supporting, opposing and periodic. In the supporting and opposing modes, the applied disturbances were generated by the controller of the disturbance motor with a constant PWM. In the periodic disturbance mode, the applied disturbance is a constant sinusoidal disturbance with varying frequency. The directions of rotation of motors in each mode are indicated by arrows in the figure 11. The experimental parameters of the tuned system are shown in table 1.

The velocity responses for three types of disturbances were plotted against time and shown in below figures, from figure 12 to figure 17..

Figure12-15. the graphs show the velocity responses correspond to with and without DOB. Moreover, figure 12 and 13 show the response of the system for supporting disturbance and figure 14. and 15. A frequency variation in the system response is due to the feedback component of the controller. When the supporting disturbance is applied with a higher frequency, the DOB

Table 1 : The experimental parameters

Parameter	Symbol	Value	Units
Motor Inertia	J_n	0.268	$Kgcm^2$
Torque coefficient	K_t	13.4	Ncm/Amp
Proportianal constant	K_p	0.07	rad/sec
Integral constant	K_i	$10^{(-7)}$	rad/sec
Derivative Constant	K_d	0.09	rad/sec
Cut-off frequency of low pass filter	G_{dis}	100	Hertz

Table 2 : DC motor specifications

Parameter	Value	Units
Rated output	0.2	kW
Rated/max. torque	20.5/169.5	Ncm
Ecoder resolution	25000	Pulses/rev

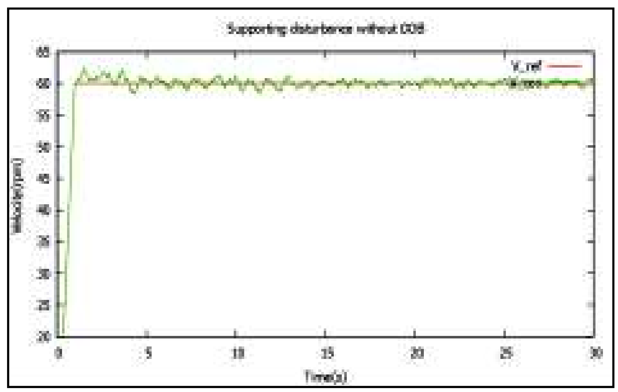

Figure 12: Supporting disturbance without DOB

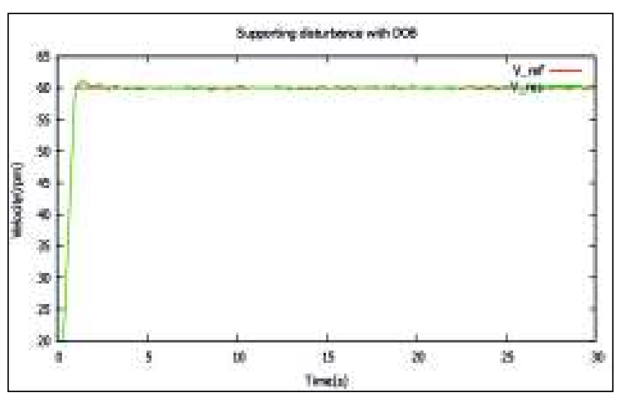

Figure 13: Supporting disturbance with DOB

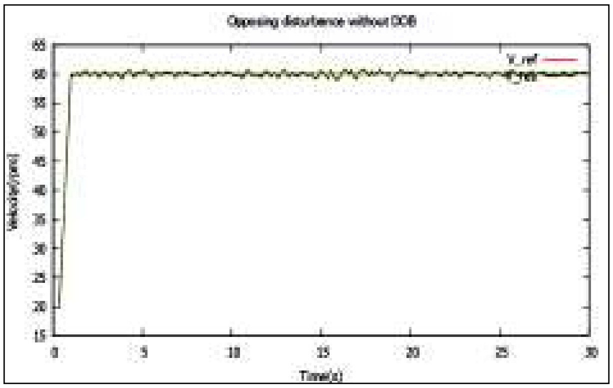

Figure 14 : Opposing disturbance without DOB

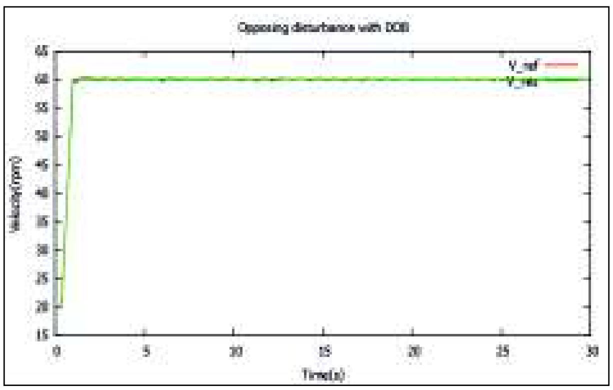

Figure 15 : Opposing disturbance with DOB

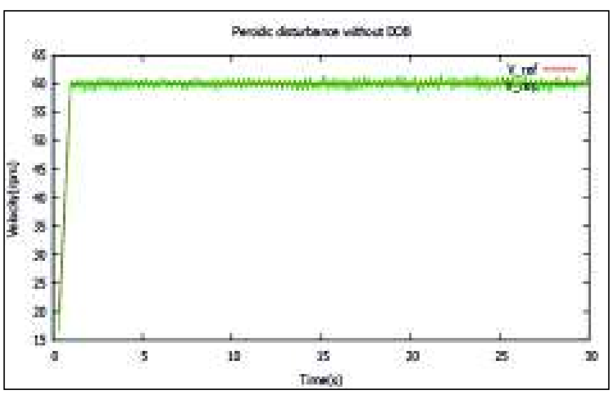

Figure 16 : Periodic disturbance without DOB

compensates it and finally results in a slightly oscillating response. For the opposing and periodic disturbances also, the system responses is similar.

In all the three cases, the velocity responses of the system clearly show the improved performance when the DOB is applied. The responses of the system closely follow

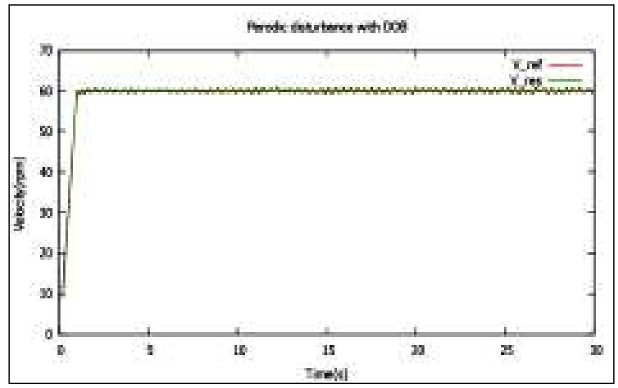

Figure 17 : Periodic disturbance with DOB

the reference velocities and the effect of the external disturbances are almost cancelled out.

CONCLUSION

In this paper, a velocity controlling mechanism for a brushed DC motor was proposed. The stability of the system was analyzed using root locus methods. The system with DOB showed a higher degree of stability compared to the only PID based system. In order to check the system responses, the experiment was conducted with different types of disturbances. Further, these responses were analyzed with and without DOB. The system response increases when the DOB is incorporated to the PID based system. Since disturbance observer compensates for load variations, friction and modeling errors, system response has become highly robust as seen in the results. When the observer gain is increased, it results in high frequency variations of the motor torque. DOB based velocity controller is more suitable for DC motors which are subjected to high disturbances and using under nonlinear conditions. Also, this technique can be used for parameters estimation, friction components identification of dc motor etc.

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