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Observer-Based Control Design for DC Servo Motors: Pole Placement and State Estimation for Enhanced Time Response and Stability Margins

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Abstract
Nowadays, both state and frequency methods have their places in the control engineer's design kit. In most cases, the frequency domain is a better way to define specifications. On the other hand, it appears that the state methods are suited to numeric work. This paper shows the linkages between the two. Pole placement requires that the whole state vector be available, a condition that is often not met in practice. This paper proposes a dynamic system called an observer to generate estimates of the states. Observer-based control has been applied to the control of a DC servo motor, where the estimates of angular position, the angular velocity and the armature current are used to generate the control signal. In this paper, we studied a design method that is fundamentally different from the classical methods. In state feedback, the controls are generated as a linear combination of the state variables. Observer-based controller has been successfully used to control a DC servo motor. The controller poles are selected to give good time response specifications and good stability margins.

Keywords: State Estimation, DC Servo Motor Control, State Feedback, Pole Placement Method.

تصميم التحكم المعتمد على المراقب لمحركات السيرفو ذات التيار المستمر: تحديد الأقطاب وتقدير الحالة لتحسين الأداء الزمني وهوامش الإستقرارية

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الملخص:
في الوقت الحاضر، تحتل كل من طرق المجال الزمني وطرق المجال الترددي مكانة مهمة في أدوات تصميم مهندس التحكم. في معظم الحالات، يُعتبر المجال الترددي الطريقة الأفضل لتحديد المواصفات. من ناحية أخرى، تُعد طرق الحالة أكثر ملاءمة للأعمال العددية. يُبرز هذا البحث الروابط بين الطريقتين. تتطلب طريقة تحديد الأقطاب (Pole Placement) توفر المتجه الكامل للحالة، وهو شرط لا يتحقق غالباً في التطبيقات العملية. يقترح هذا البحث استخدام نظام ديناميكي يُعرف بـ "المراقب" (Observer) لتوليد تقديرات لحالات النظام. تم تطبيق التحكم المعتمد على المراقب في نظام التحكم بمحرك سيرفو تيار مستمر، حيث تُستخدم تقديرات الموضع الزاوي والسرعة الزاوية وتيار العضو الدوار لتوليد إشارة التحكم. في هذا البحث، تم دراسة طريقة تصميم تختلف جوهرياً عن الطرق الكلاسيكية. في التغذية الراجعة للحالة، يتم توليد إشارات التحكم من خلال توليفة خطية لمتغيرات الحالة. وقد تم استخدام وحدة التحكم المعتمدة على المراقب بنجاح في التحكم بمحرك سيرفو تيار مستمر. تم اختيار أقطاب وحدة التحكم لتحقيق استجابة زمنية جيدة وهوامش استقرارية مناسبة.

الكلمات المفتاحية: تقدير الحالة، التحكم بمحرك سيرفو تيار مستمر، التغذية الراجعة للحالة، طريقة تحديد الأقطاب.

Introduction

Design of Control Systems Via State Space:

In conventional control theory, only the input, output and error signal are considered important; the analysis and design of control systems are carried out using transfer functions, together with a variety of graphical techniques, such as root-locus plot and Bode diagrams.

The main disadvantage of conventional control theory is that, generally. It is applicable only to linear time-invariant systems having a single input and a single output. It is powerless for time-varying systems, nonlinear systems (except simple ones) and multiple-input, multiple-output systems. Thus, conventional techniques (the root-locus and frequency response methods) do not apply to the design of optimal and adaptive control systems, which are mostly time-varying and/or nonlinear [1].

Systems design by conventional control theory is based on trial-and-error produced that, in general, will not yield optimal control systems. System design by modern control theory via state space methods, on the other hand enables the engineer to design such systems having desired closed-loop poles (or desired characteristic equations) or optimal control systems concerning given performance indexes. Also, modern control theory enables the designer to include the initial condition. If necessary, in the design.

However, design by modern control theory (via state space methods) requires accurate mathematical descriptions of systems dynamics. This is in contrast to the conventional methods, where. For example, experimental frequency-response curves that may not have sufficient accuracy can be incorporated in the design without their mathematical descriptions [2].
From the computational viewpoint, the state-space methods are particularly suited for digital-computer computation because of their time-domain approach. This relieves the engineer of the burden of tedious computations otherwise necessary and enables him to devote his efforts solely to the analytical aspects of the problem. This is one of the advantages of the state-space methods [3][4].
Finally, it is important to note that it is not necessary that the state variable represent physical quantities of the system. Variables that do not represent physical quantities and those that are neither measurable nor observable may be chosen as state variables. Such freedom in choosing state variables is another advantage of the state-space methods.
Pole Placement Design and Design of Observers:
In this paper, we shall present one approach to the design of a regulator. Regulator systems are feedback control systems that will bring nonzero states (caused by external disturbances) to the origin with a sufficient speed. This approach to design regulator systems is to construct an asymptotically stable closed-loop system by specifying the desired locations for the closed-loop poles. This may be accomplished by use of state feedback; that is, we assume the control vector to be $u = - Kx$ (where u is unconstrained) and determine the feedback gain matrix k such that the system will have a desired characteristic equation. This design scheme is referred to as pole placement.
The pole placement approach requires the feedback of all state variables. Therefore, it becomes necessary that all state variables be available for feedback. However, some state variables may be measurable and may not be available for feedback. Then we need to estimate such unmeasurable state variables by use of state observers.
It is noted that it will be shown later that pole placement is not possible if the system is not completely state controllable. Design of state observers (that are required in many state feedback schemes) is not possible if the system is not observable. Hence, controllability and observability play an important role in the design of control systems.

Literature Review

The application of observer-based control strategies in DC servo motor systems has attracted significant attention due to their effectiveness in systems where full state measurement is either impractical or costly. These strategies combine state estimation with state feedback control, allowing improved performance, robustness, and reduced hardware complexity.

Patel et al. [10] proposed a full-order observer-based control strategy for DC motors, emphasizing accurate state estimation when certain state variables are not measurable. Their simulation results demonstrated fast convergence of the observer and significant enhancement in speed control, especially in transient conditions.

In a complementary direction, Rahman, Choudhury, and Mahmud [11] explored a sensorless DC motor control scheme using optimal observer-based servo control. Their work focused on reducing the reliance on physical sensors, which is particularly beneficial in applications with stringent space or cost constraints. The system retained strong stability and tracking accuracy despite the absence of direct measurements.

Okoro and Enwerem [12] compared classical and modern control strategies for DC motors and highlighted that observer-based state feedback systems outperformed traditional PID controllers in terms of response time, overshoot reduction, and robustness. They concluded that observer-based approaches are more suitable for advanced applications requiring precise control.

In an experimental study, Rahman et al. [13] designed and implemented an observer-based state feedback controller using an identified motor model. The study underscored the importance of accurate model identification for reliable state estimation and showed the practical viability of implementing observer-based controllers in real-world setups.

Further improvements were explored by Mokhtar et al. [14], who integrated an extended Kalman filter as an observer in a fault-tolerant control framework. Their system maintained performance and stability even in the presence of sensor faults, validating the robustness of advanced observer-based designs.

Ali and Ghoneim [15] focused on tuning a Luenberger observer for permanent magnet DC motors. Their findings revealed that proper selection of observer poles significantly influenced the accuracy of state estimation and improved the overall dynamic response of the system.

Yao et al. [16] combined model predictive control with observer-based estimation for DC drive systems. This integration allowed for real-time constraint handling and improved performance in the presence of external disturbances, showing the versatility of observer-based control within advanced control frameworks.

Lastly, Tran et al. [17] developed a reduced-order observer for real-time embedded control in mobile robotics applications. They emphasized the importance of computational efficiency and showed that observer-based control strategies could be implemented in low-latency embedded systems without compromising estimation precision.

Collectively, these studies affirm the critical role of observer-based control in modern DC servo motor applications. They highlight its ability to enhance control performance, ensure system stability, and offer robustness against uncertainties—all while minimizing the need for additional hardware sensors.

Material and methods:
Design of the Observer
The observer model is given by:

$$\dot{\hat{x}} = A\hat{x} + Bu + l(y - C\hat{x})$$

Where,

$\hat{x} = \begin{bmatrix} \hat{\theta} \\ \hat{\omega} \\ \hat{\imath} \end{bmatrix}$ = estimated state vector. $A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 4.483 \\ 0 & -12 & -24 \end{bmatrix}$, $B = \begin{bmatrix} 0 \\ 0 \\ 20 \end{bmatrix}$ and $C = [1 \quad 0 \quad 0]$

The observer gain matrix $l = \begin{bmatrix} l_1 \\ l_2 \\ l_3 \end{bmatrix}$ depends on the specified eigenvalues of the error system.

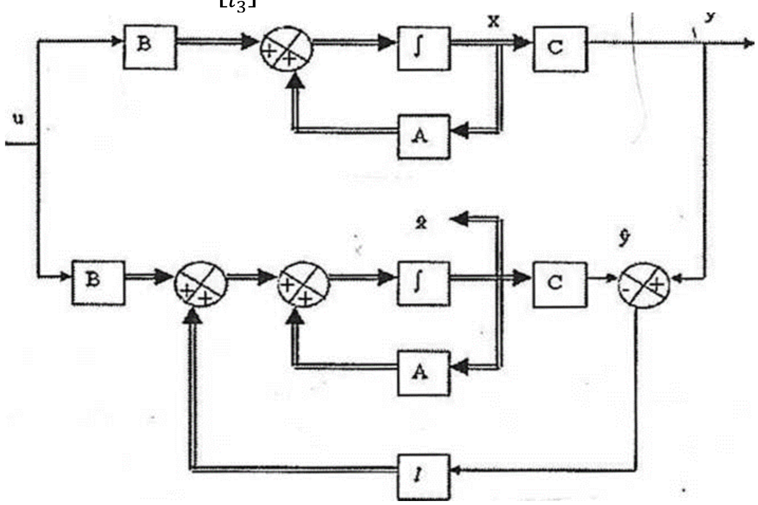

Figure 1: Shows the block diagram of the observer.

Figure 2, Figure 3 and Figure 4 show the actual and the observed angular position θ for eigenvalues (-5 ± j5 and -7), (-0.5 ± j5 and -7) and (-5 ± j5 and 7), respectively.

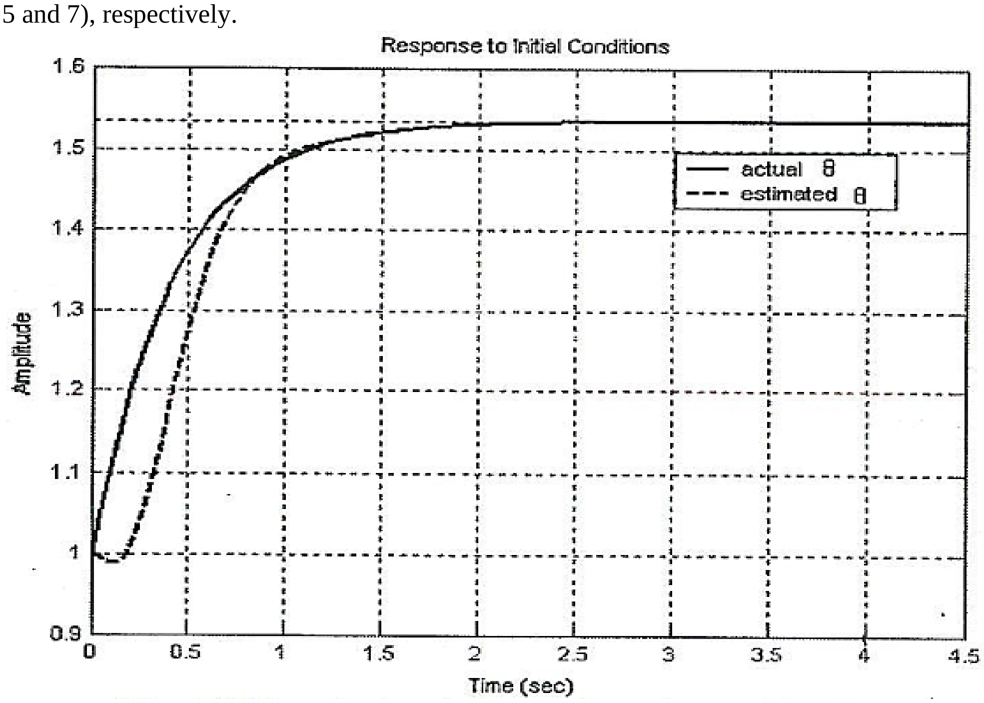

Figure 2: The actual and observed angular position θ for eigenvalues (-5 ± j5 and -7).

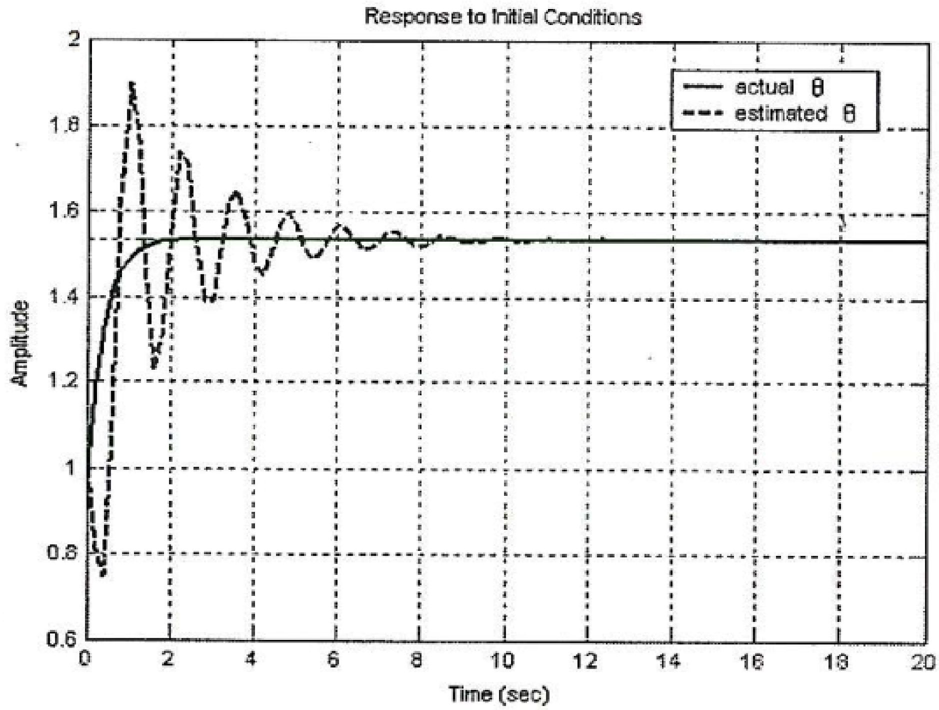

Figure 3: The actual and observed angular position θ for eigenvalues (-0.5 ± j5 and -7)

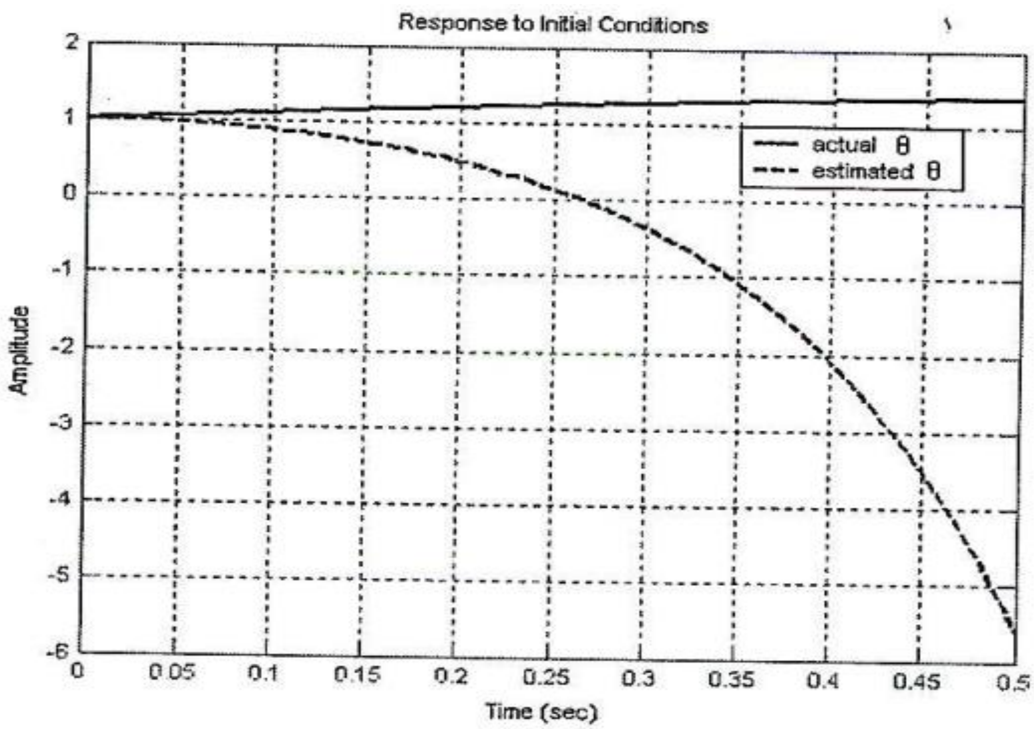

Figure 4: The actual and observed angular position θ for eigenvaiues (-5 ± j5 and 7)

The eigenvalues of the error system are selected to be -5 ± j5 and -7 as it gives a good performance for the observer. The observer gain matrix l is found to be

$$l = \begin{bmatrix} -7 \\ 234.7 \\ -1106.6 \end{bmatrix}$$

Figures 5, 6 and 7 show the time responses of the actual and observed states for θ, ω and i, respectively.

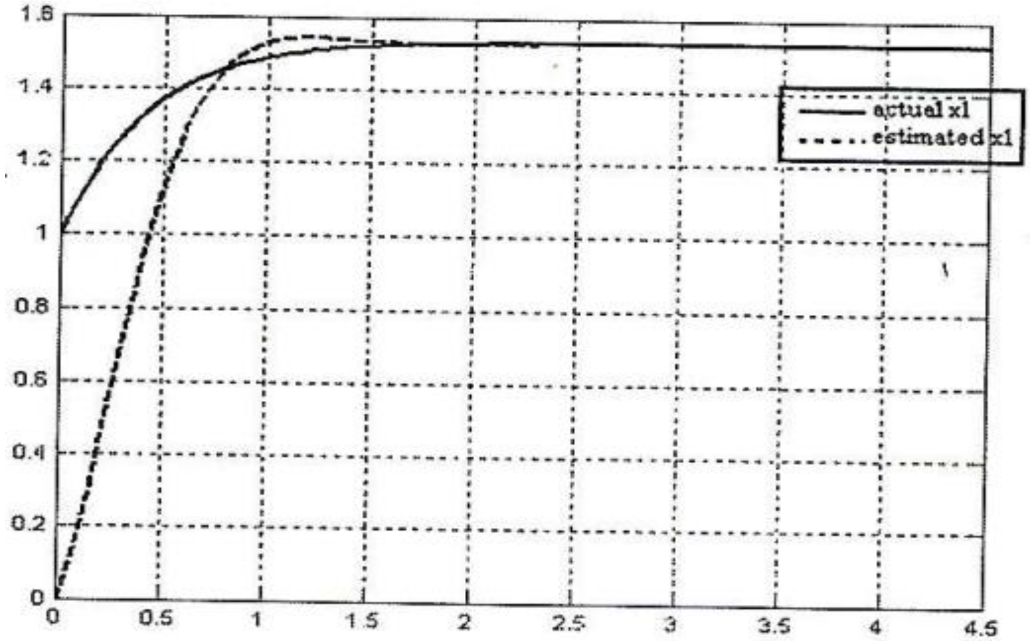

Figure 5: Time response of the actual and observed state $x_1(\theta)$ with initial condition [1   0].

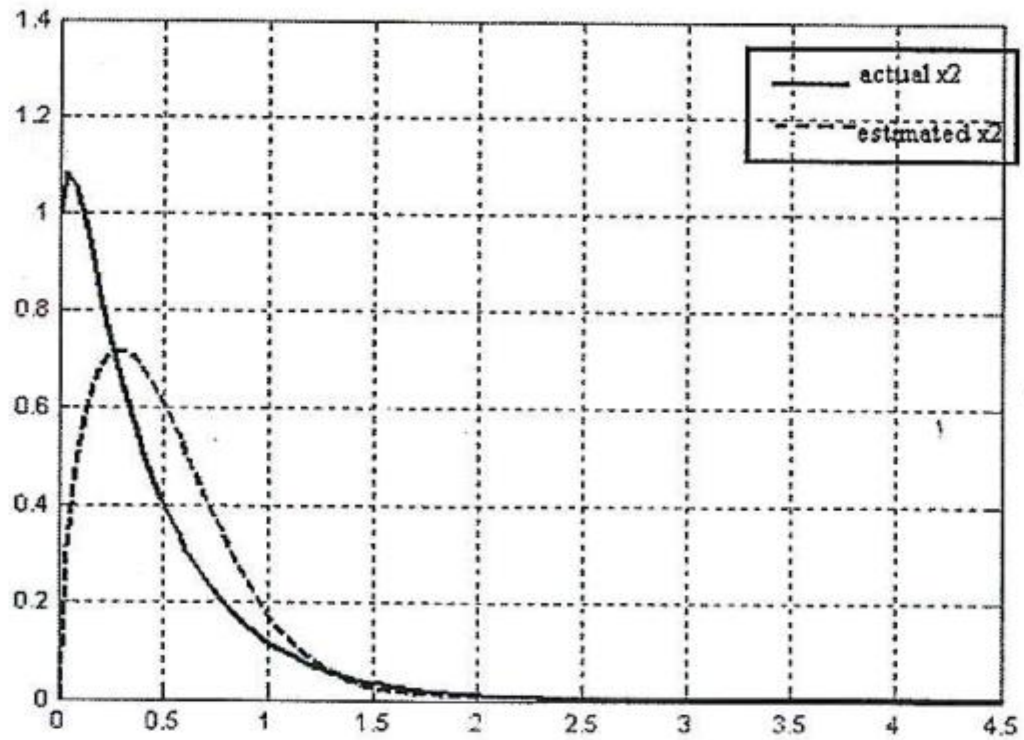

Figure 6: Time response of the actual and observed state $x_2(\omega)$ with initial condition [1   0].

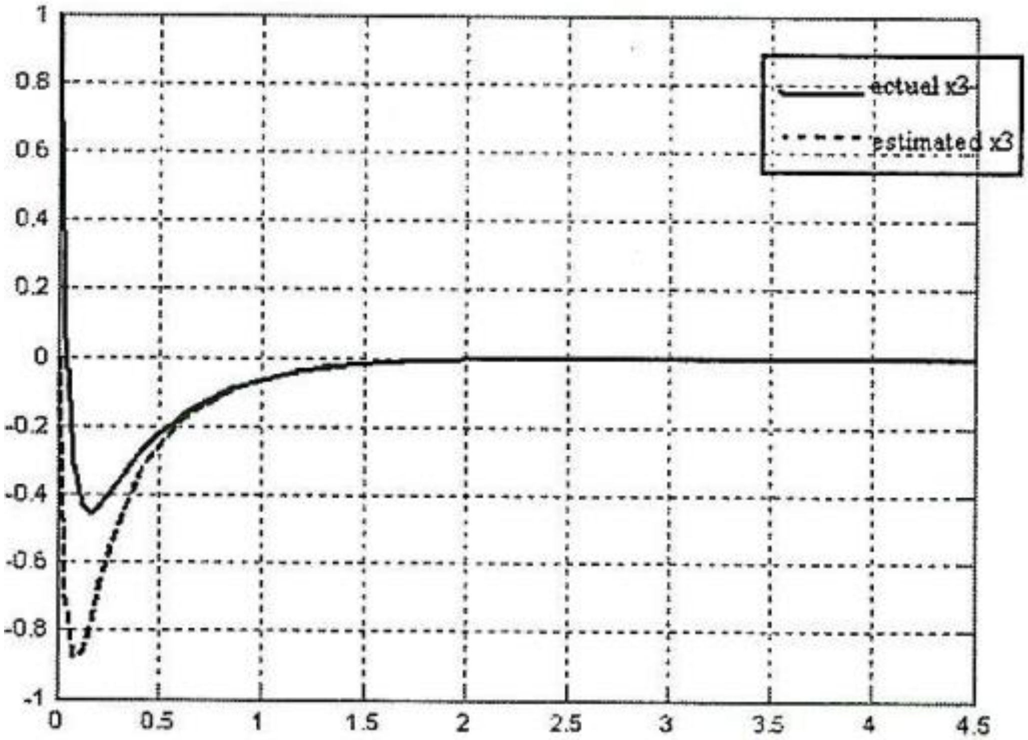

Figure 7: Time response of the actual and observed state $x_3(i)$ with initial condition [1   0].

Design of the Controller:
Figure 8 shows the block diagram of the control system with the observer.

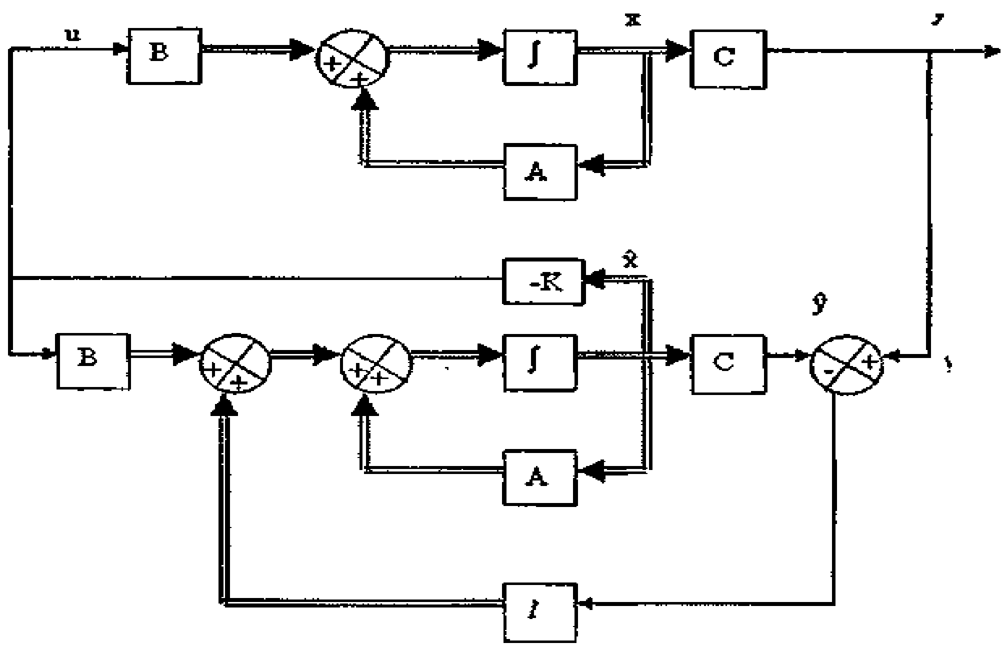

Figure 8: Block diagram of the control system with the observer.

It can be verified that the system is controllable. Different closed-loop poles for the design of the controller are tested.
The time responses for angular position of the observed control system for different closed-loop poles locations are shown in Figure 9. The frequency responses for different closed-loop poles locations are shown in Figure 10. The time responses and frequency responses specifications for the different closed-loop poles locations are recorded in Table 1.

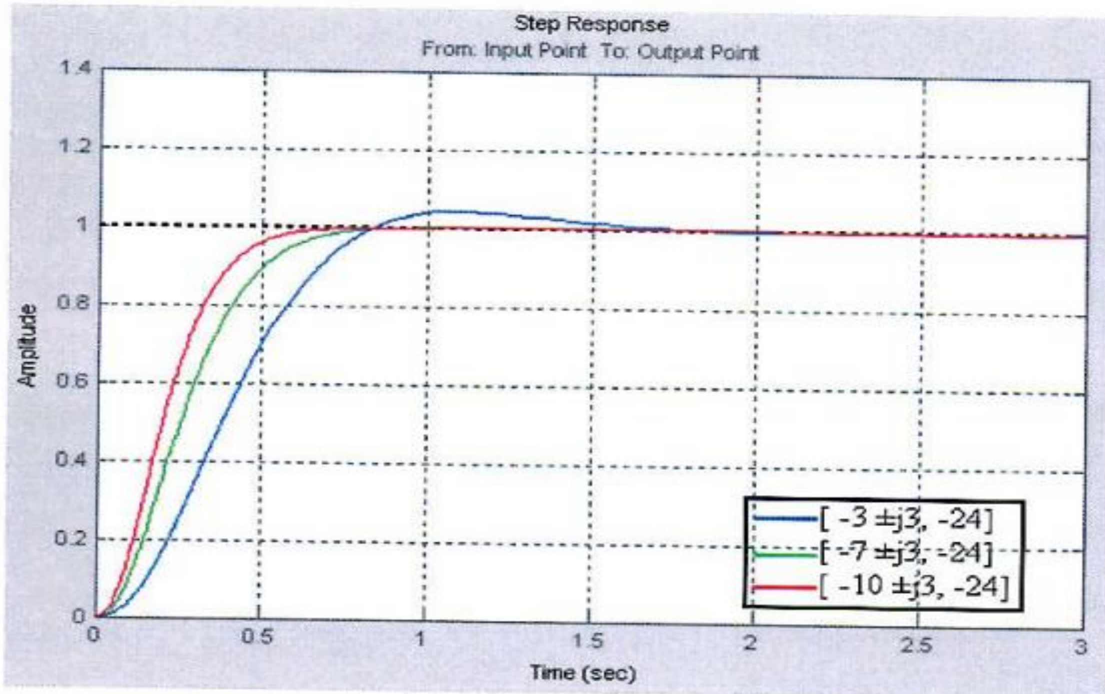

Figure 9: Step response for angular position of the observed control system for different closed loop poles locations.

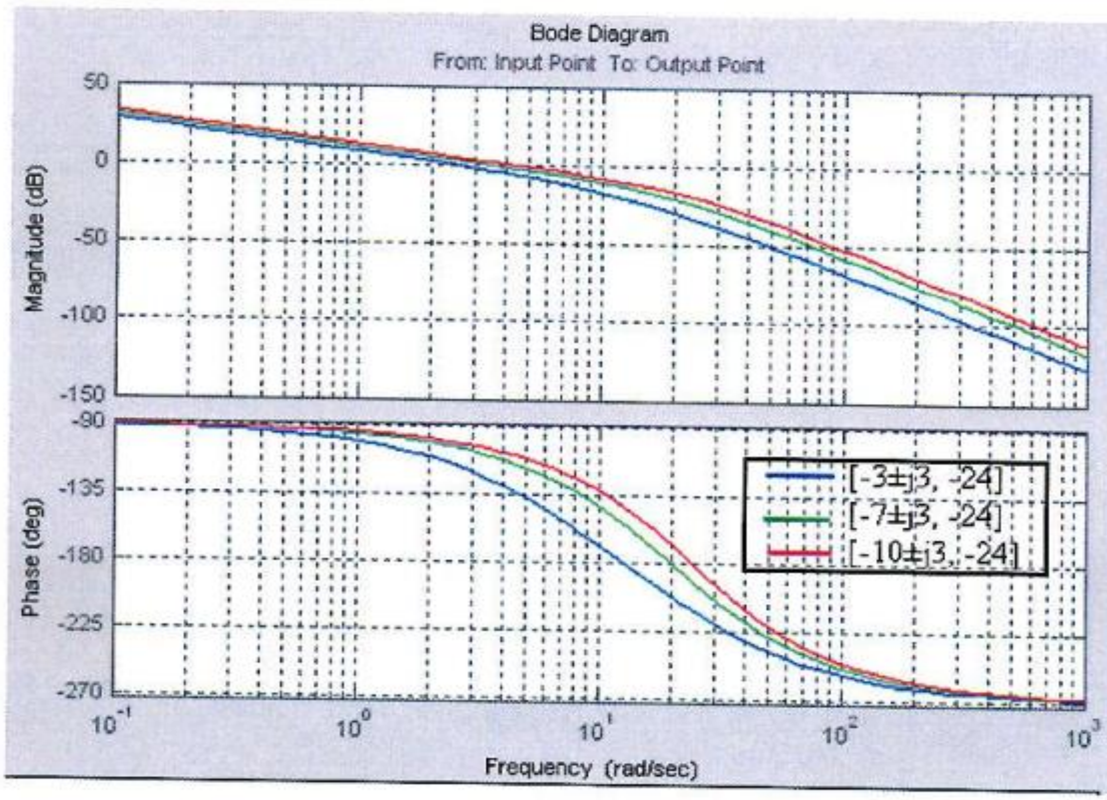

Figure 10: Frequency response for angular position of the observed control system for different closed loop poles locations

Table 1: Time responses and frequency responses specifications for the angular position of the observed control system for the different pole locations

	Time domain			Frequency domain	
Desired poles	Rise time (sec)	Overshoot (%)	Settling time (sec)	Gain margin (sec)	Phase margin (degree)
-3±j3 and -24	0.516	4.24	1.45	21	64.3
-7±j3artd -24	0405	0.06	0.695	20.6	71.1
-10±j3 and -24	0321	0	0.566	19.9	71.4

The desired closed loop poles are selected to be -10 ± j3 and -24. These poles give good rise time, settling time, gain margin and phase margin Figure 11 shows the time response for angular position θ obtained from the observed control system using the desired closed loop poles locations shown above.

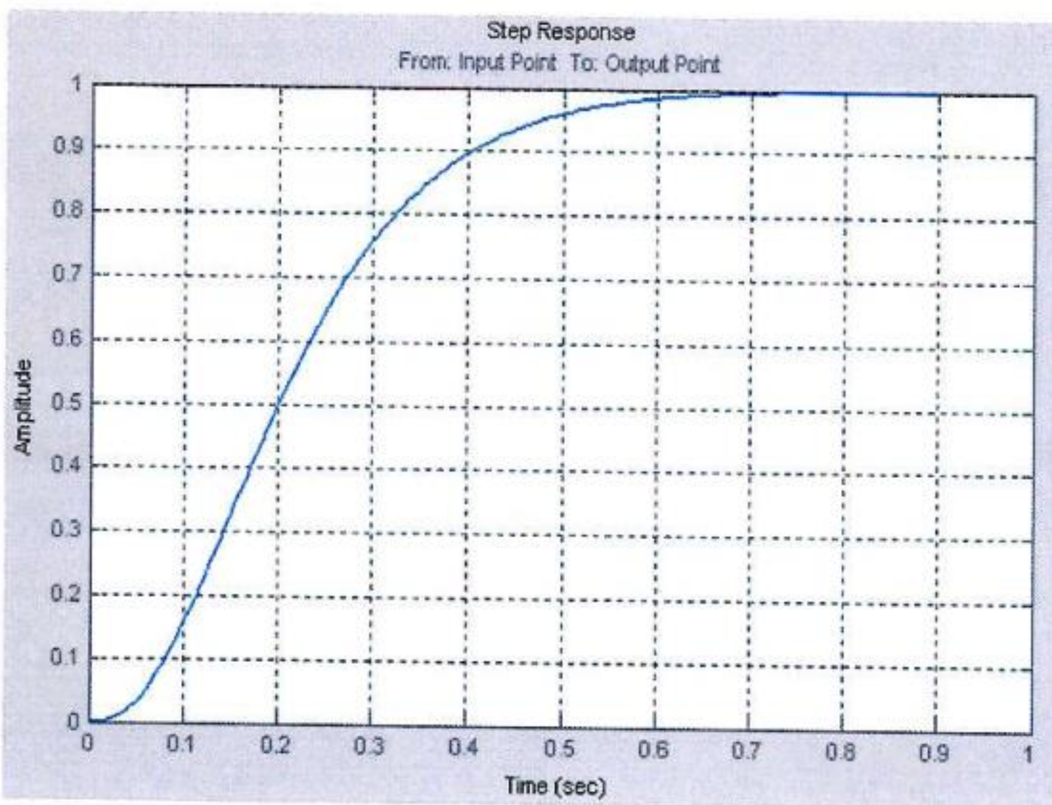

Figure 11: Step response for angular position using the desired closed loop poles locations -10 ± j3 and -24.

The gain matrix of the controller is:
k = [29.4727 6.0359 1.0000]
The control law is given by:
u(t) = 29.4727 $(\theta_d - \theta)$ - 6.0359ω - i
For observed control system the control law becomes:
u(t) = -k$\hat{x}$
= 29.4727$(\theta_d - \hat{\theta})$ - 6.0359$\hat{\omega}$ - $\hat{\imath}$

The block diagram of the observed control system is shown in Figure 12.

The simulation of the observed control system by MATLAB is shown in the appendix.

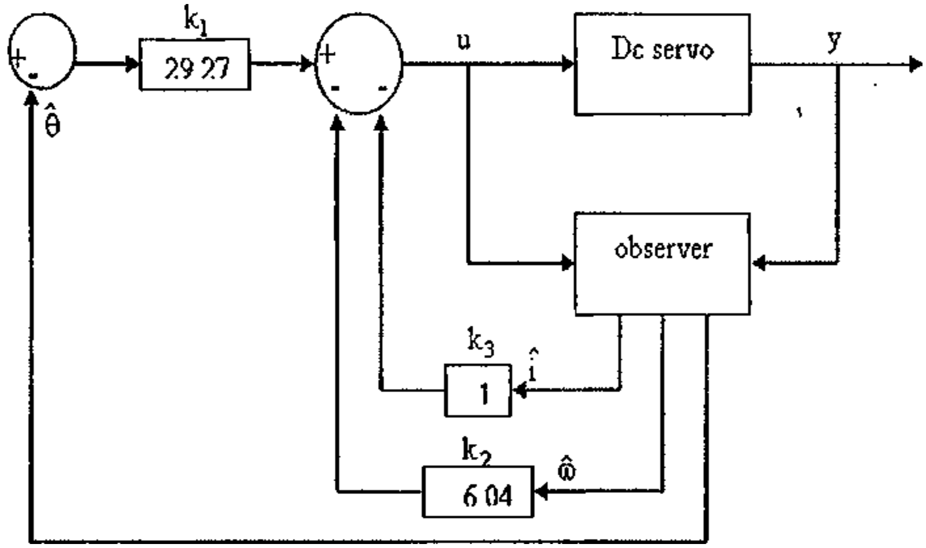

Figure 12: The block diagram of the observed control system.

Results and discussion

The effect of motor parameter changes on the performance of the controller is studied. Figure 13 shows the time responses of the observed control system when the motor parameters R (armature resistance) and J (inertia) are changed from (1.2Ω and 0.02Kgm^2) to (1.3Ω and 0.03Kgm^2), (1.1 Ω and 0.03Kgm^2) and (1.3 Ω and 0.01Kgm^2), respectively. Figure 14 shows the frequency responses of the control system for different variations in armature resistance R and inertia J.

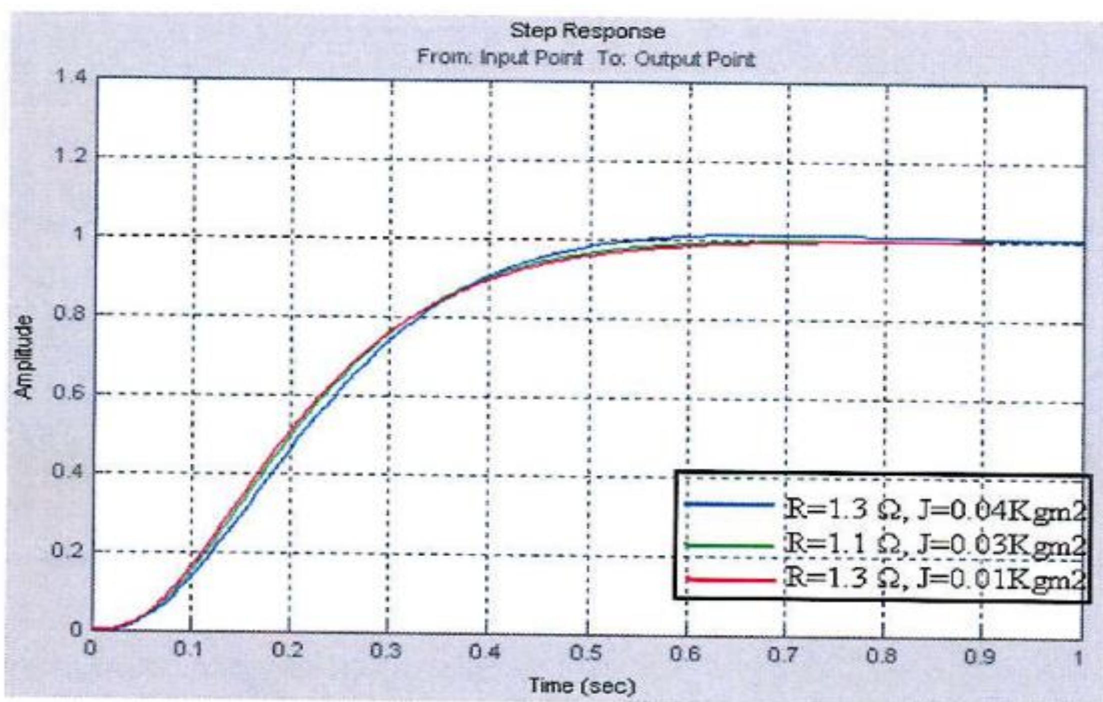

Figure 13: Step response of the observed control system for different changes in motor parameters R and J.

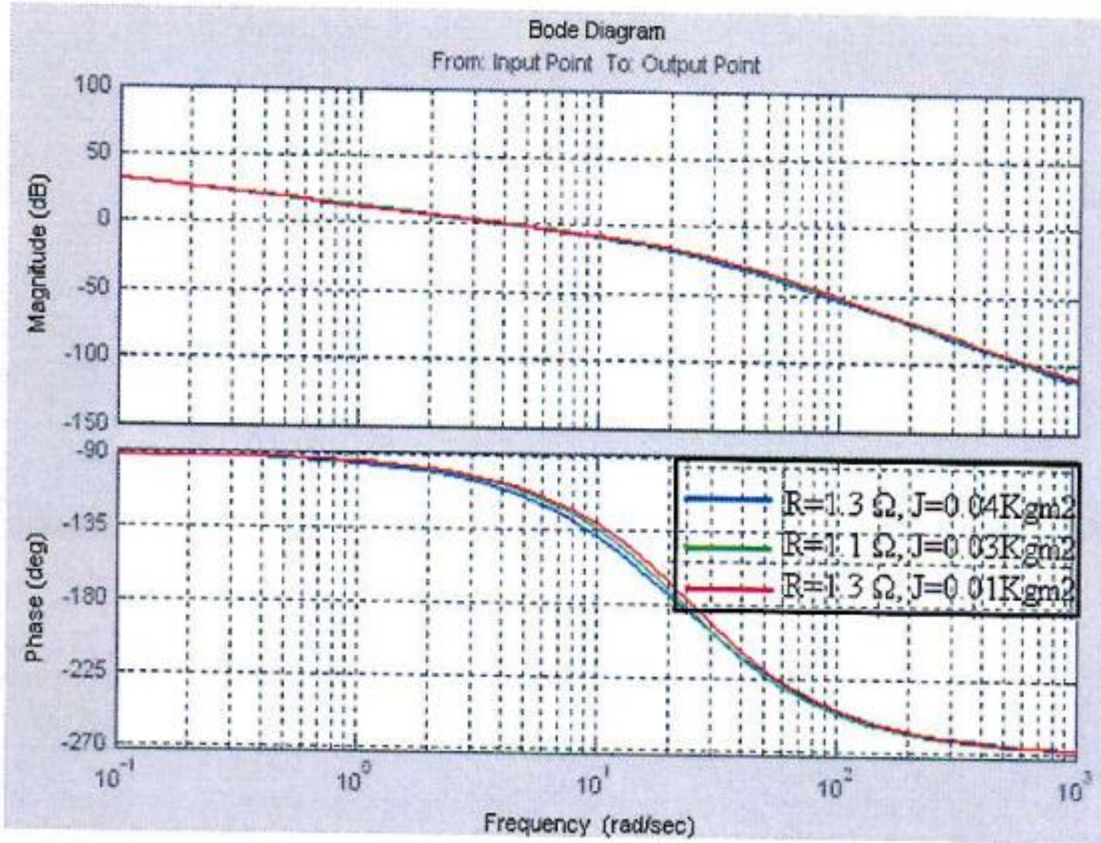

Figure 14: Frequency response of the observed control system for different changes in motor parameters R and J.

Table 2: shows the time domain and frequency domain specifications of the observed control system for different changes in motor parameters R and J.

	Time domain			Frequency domain	
Motor parameters	Rise time (sec)	Overshoot (%)	Settling time (sec)	Gain margin (db)	Phase margin (degree)
No Variation	0.321	0	0.565	19.9	71.4
R=1.3 & J=0.04	0.311	1.14	0.499	20.3	68.3
R=1.1 & J=0.03	0.317	0.06	0.554	19.5	71
R=1.3 & J=0.01	0.326	0	0.58	20.3	71.8

The effect of changes in motor parameter K_m is also shown. Figure 15 and Figure 16 show time responses and frequency responses for different changes in motor parameter K_m. The resulting time domain and frequency domain specifications for different changes in K_m are recorded in Table 3.

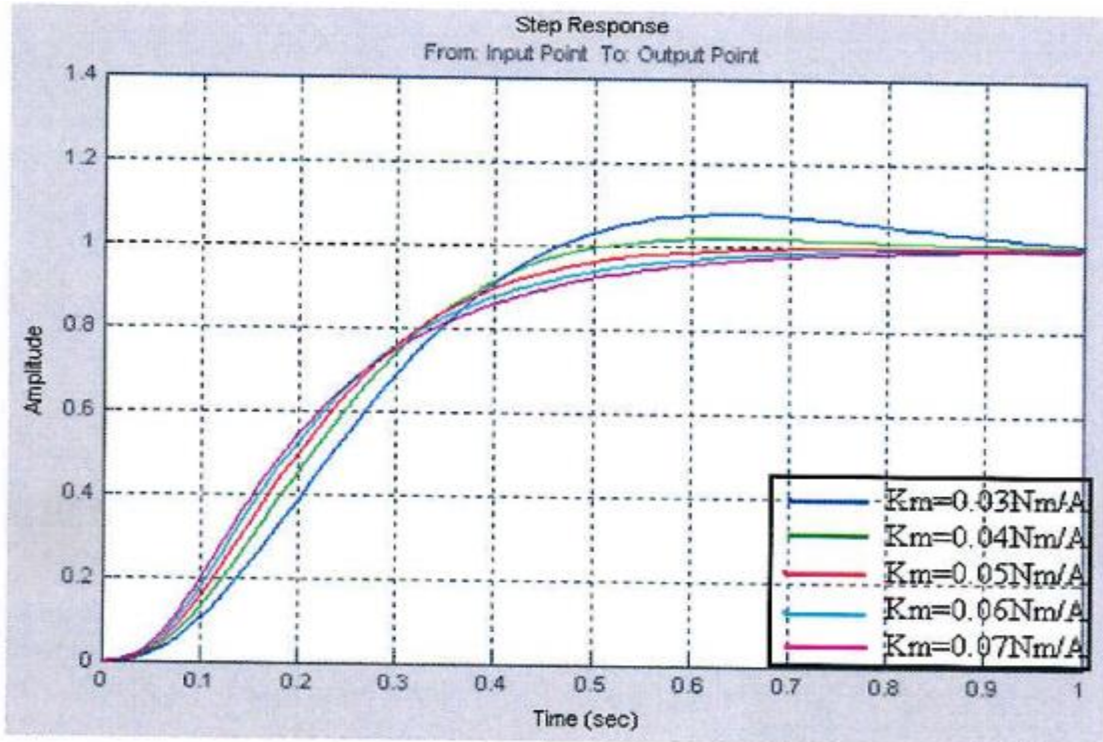

Figure 15: Step response of the observed control system for different changes in motor parameters K_m.

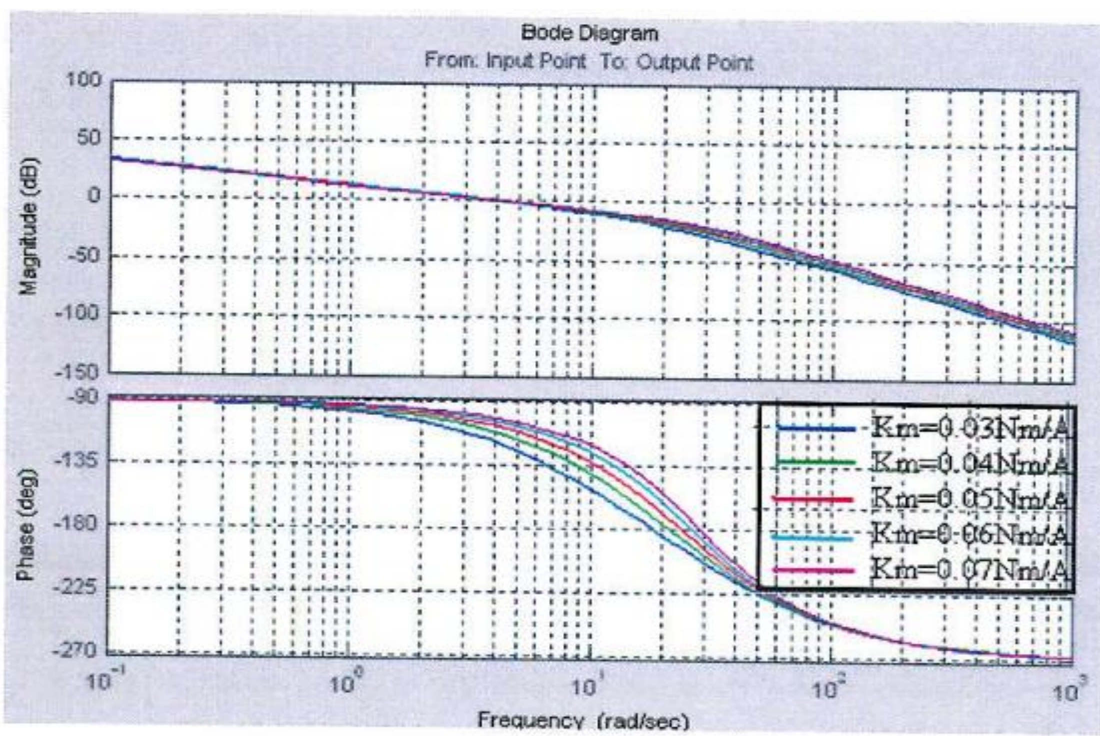

Figure 16: Frequency response of the observed control system for different changes in motor parameters K_m.

Table 3: Specifications of the observed control system for different changes in motor parameters.

	Time domain			Frequency domain	
Km	Rise time (sec)	Overshoot (%)	Settling time (sec)	Gain margin (sec)	Phase margin (degree)
0.03	0.297	7.83	0.932	19.6	60.1
0.04	0.3	2.09	0.684	19.8	66.8
No Variation	0.321	0	0.565	19.9	71.4
0.06	0.355	0	0.672	20.1	74.8
0.07	0.387	0	0.737	20.2	77.3

Conclusion

Controller design via state-space technique consists of feeding back the state variables to the input u, of the system through specified gain. In some cases the control signal can not affect on all state variables. For this system, a total design is not possible. Using the controllability matrix, a designer can tell whether or not a system is controllable prior to the design.

State feedback gives the designer the option of relocating all system closed loop poles. This is in contrast with classical design, where by the designer can only hope to achieve a pair of complex conjugate poles that are dominate. Because all other poles and zero may fall anywhere, mating the design specifications becomes a matter of trial and error. With the freedom of choice render by state feedback comes the responsibility of selecting these poles judiciously.

Observer design consist of feedback the error between the actual output and the estimated state variables. The response of the observer is designed to be faster than the controller, so the estimated state variables effecting appear instantaneously at the controller. For same systems, as is require by the observer. Using the observability matrix, the designer can tell whether or not a system is observable. Observers can be designed only for observable systems.

Three advantages of state-space design are apparent. First, in contrast to the Root locus method, all poles locations can be specified to ensure negligible effect of the none dominate poles upon the transient response. Second, with the use of an observer, we are no longer forced to acquire the actual system variables for feedback. The advantage here is that sometimes the variables can not by physically accessed, or it may be too expensive to provide that access. Finally, the methods shown lend themselves to design automation using the digital computer.

Observer-based controller has been successfully used to control a de servo motor. The controller poles are selected to give good time response specifications and good stability margins. The controller works on the observed angular position, the observed angular velocity and the observed current. The observer was simulated to verify its convergence. We have a complete freedom in the controller and observer poles selection. The separation between the control and the observer problem leads to design the controller assuming the states (angular position, velocity and current) are available, design an observer to estimate the states, and use the estimates in place of the actual states. It is shown that the observer-based controller is robust against variations in motor parameters.

This work is far from complete in the sense that many interesting points may discussed and studied such as adding an integral term to the observer model, resulting PI observer. This topic may be subject of a forthcoming work

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