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Research Article

Modeling and Control of a Novel Permanent Magnet Linear Motor

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ABSTRACT

This paper concerns on modeling and linear controller design of a novel permanent magnet DC linear motor. The paper first introduces the novelty of designed and implemented motor, and then presents its dynamical model. By using the developed model, a linear controller has been designed and the results of the numerical simulation of the designed controller have been presented to show the effectiveness and stability of the designed controller. Some future prospects for the designed and simulated controller have also been provided.

Keywords: *Permanent Magnet DC Linear Motors, Controller Design, Simulation*

Yeni Bir Kalıcı Mıknatıslı Lineer Moturun Modellenmesi ve Kontrolü

ÖZ

Bu çalışma, yeni bir kalıcı mıknatıslı DC lineer motorun modellenmesi ve bu motor için lineer kontrolör tasarımı üzerinedir. Makalede ilk önce, tasarlanan ve üretilen yeni motor tanıtılmış ve motorun dinamik modeli elde edilmiştir. Geliştirilen bu model üzerinden bir lineer kontrolör tasarlanmıştır ve daha sonra tasarlanan kontrolörün etkinliğini ve kararlılığını göstermek amacıyla nümerik simülasyon sonuçları sunulmuştur. Son olarak da bu kontrolör bazı gelecek önerileri sunulmuştur.

Anahtar Kelimeler: *Kalıcı Mıknatıslı DC Lineer Motorlar, Kontrolör Tasarımı, Simülasyon*

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I. INTRODUCTION

Electric motors convert electrical energy into mechanical motion. Conventional rotary motors produce rotary motion. If linear motion is needed, then there are two basic options; either using some equipment like gears and belts to convert rotary motion into linear motion, or using directly a linear motor. Either options have some advantages and disadvantages, for example, the gears and belts bring mechanical losses and extra costs while the linear motors bring stroke limitations. Less force/current ratio compared to the conventional rotary motors is another disadvantage of the linear motors. To contribute overcoming such limitations, a completely new linear motor has been proposed [1] and patented [2]. It has no stroke limitations and also high force/current ratio. To clearly reveal the advantages this motor offers, a useful review of the pertinent available literature on the linear motors have been provided below.

Linear motors are widely used in industry. Some areas of applications are 3D printers [3], maglev trains [4], elevators [5], CNC systems [6], and automatic doors [7]. Just like the rotary motors, the linear motors can be classified as DC Linear Motor, AC Linear Motors, and Synchronous Linear Motors. First DC Linear Motor is proposed in 1964 [8]. But there were wounds on both rotor and stator in this motor, i.e., no permanent magnets had been used. Starting from 1970's, permanent magnets have been widely used in the linear motors since they reduce motor volume, increase the motor efficiency, and lead to less cost for fixed force value. Figure 1 shows a basic sketch of a moving-magnet DC Linear Motor, which is called a single-sided DC Linear Motor, since permanent magnets are placed on only one side of the stator, the stationary part [1]. If another group of the permanent magnets are placed on the other side of the stator to produce higher force, this configuration is called double-sided. The configuration in Figure 1 is also called flat, since it is geometry is flat, but if both stator and rotor is produced in a tubular geometry to produce higher force, this is called a permanent magnet tubular DC Linear Motor.

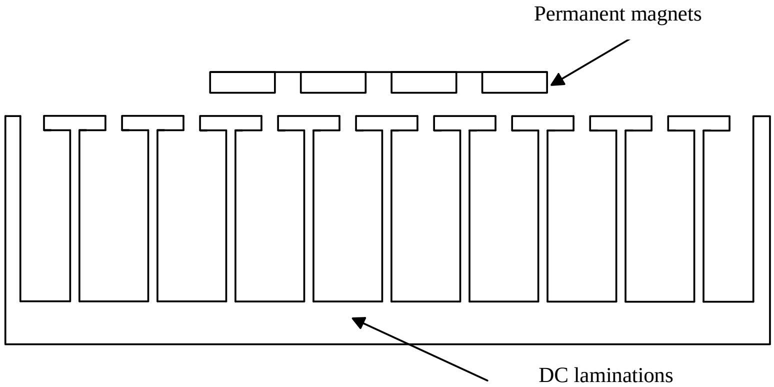

Figure 1. *A sketch of a permanent magnet DC linear motor*

The principal benefit that a linear motor offers is the elimination of the extra equipment to convert rotary motion into linear motion. But, on the other hand, there are some disadvantages of this type of motors. Besides the some other disadvantages, historical development of the DC linear motors dictates two basic disadvantages; (1) low force-current ratio, (2) limitation on motor stroke (length of the stator). The first permanent magnet DC Linear Motor has been proposed by Basak in 1975 [9]. This motor has a length of 45 cm, and produces 1.5 N force per 1 A. These two values are especially important to explain both improvements in permanent magnet DC linear motor technology and the benefit of the motor to be controlled in this study. It is especially because that these values are quite low and many researchers have focused on the design and implementation of novel DC Linear Motors to improve these values. To contribute these improvement efforts, several motors of same type used in this study have been proposed and their force/current ratios have been reported. For example, for 1 A current, the developed force is 2.67 N in [10], 27 N in [11], 1 N in [12], 7.8 N in [13], 1 N [14], and 24 N in [15]. A very recent study [16] reports generation of 27 N force per ampere. Reported experimental results clearly show that there is still a need to improve force/current ratio for this type of motor to be able use them for some special applications like electromagnetic launchers.

In 2023, a completely novel permanent magnet DC linear motor has been designed, implemented and tested [1-2]. This motor has a tubular geometry, as shown in Figure 2. Moving unit, armature or rotor, has two parts; upper shaft and lower shaft, both made by using 1010 mild steel material, and includes Neodymium-Ferro-Boron permanent magnets. The armature is moving through 4 cylindrical bar via linear bearings. Stationary part, stator, again made by using 1010 mild steel material, and includes wounds. Terminals of each coil are connected to the collector, also called commutator, to carry the current flowing through coils by using brushes.

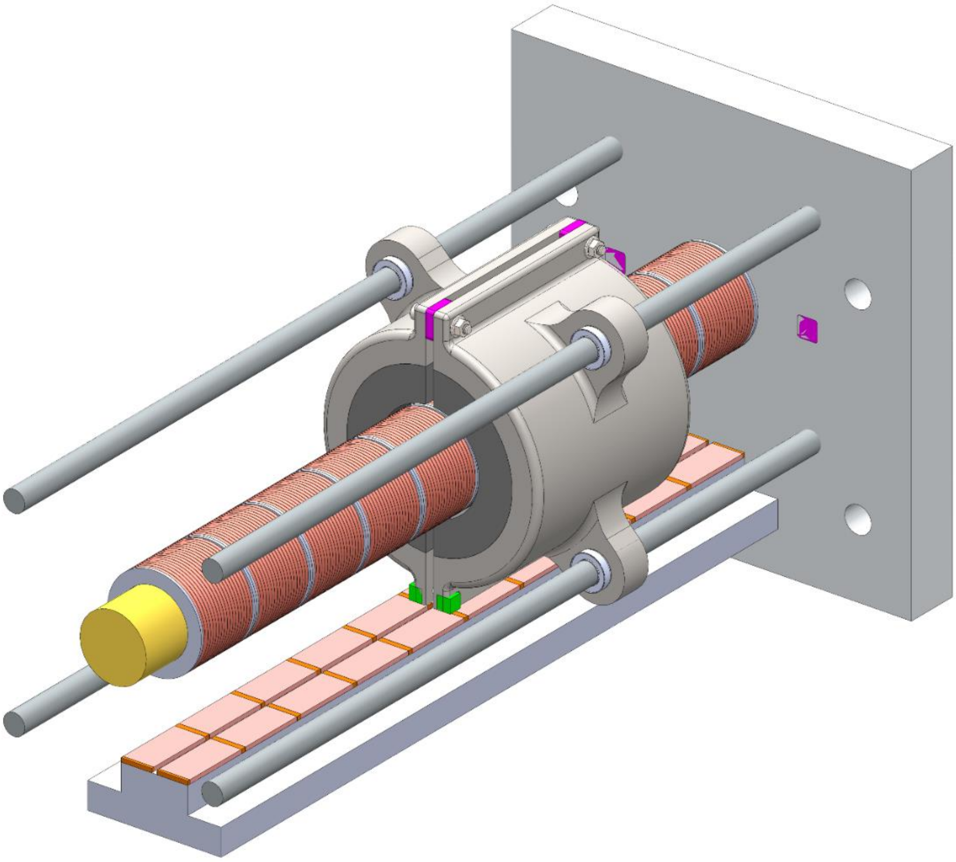

Figure 2. *A 3D sketch of a novel permanent magnet DC linear motor*

Experimental test results reported in [1] shows that the motor introduced above develops 195 N force per 1 A. Such a force/current ratio makes this motor an inspring solution to the problem of high-force need for some types of special applications. Another benefit this motor offers is drive mechanism simplicity, i.e., there is no need to complex drive circuit if the stator is fabricated longer. When more coils are used at the stator to get more stroke, only need is more collector cell instead of using complex power electronics circuits. So the introduced motor produces a solution to two basic problems of permanent magnet DC linear motors, i.e., the motor produces high force/current ratio and eliminates the complex drive mechanism to get longer stroke. More analytical, magnetic, and thermal analysis results and experimental data can be found in [17] for this motor.

Figure 3 shows an implemented form of the motor. This figure also shows the components of the test systems of the motor. The motor is supplied by a DC power source via a drive system and all the measurement results have been assigned to variable defined in MATLAB/Simulink environment. Position of the motor has been measured by a linear potentiometer, developed force has been measured by a Loadcell, and, current flowing through the armature wounds has been measured by a proper current sensor. By using the setup introduced in Figure 3, time variations of the developed force, armature current, and armature position have been recorded. Figure 4, for example, shows the developed static force versus position.

Figure 3. *Test setup*

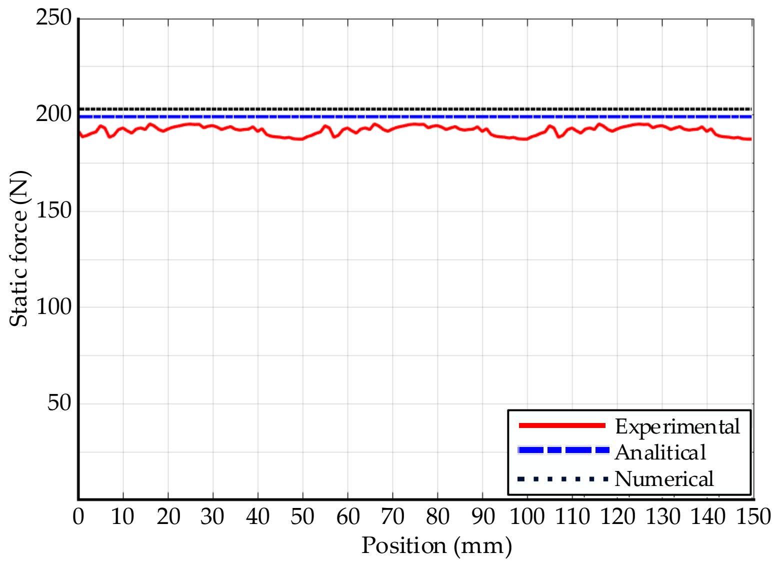

Figure 4. *Developed force with respect to position*

Figure 4 shows that numerical, analytical, and experimental results are in good compliance. The figure also shows that the developed force hits 195 N experimentally. Control of this novel motor is the main focus of this paper. Position, speed, current, and force control of the motor have potential for proving feasibility of the motor for some type of special applications. Even if there are many studies on the brushless DC linear motor control [18-23], there are only a few studies on control of brushed DC linear motor since brush mechanism brings fault risk and maintenance requirements. But, on the other hand, some special applications especially needs brushed motor. For example, DC electromagnetic launchers need a brush mechanism since the energy can not be transferred from the stationary part to moving part via induction, that is, a physical contact between two parts is a must in DC electromagnetic launchers. For this reason, brushed DC linear motors need more effort on control of position, speed, current, and force to prove the performance and feasibility of this type of motors for some special applications like DC electromagnetic launchers.

The rest of the paper is organized as follows: Chapter II defines the control problem by introducing the system model. It is important to point out that only linear control design by using a linear model of the system will be used in this study. Nonlinear control of the motor is out of scope of this study. Chapter III presents a controller design by using a linear model. Chapter IV provides an observer design. Numerical simulation results of the designed controller and observer are given in Chapter V. The last section concludes all the results with some future prospect.

II. CONTROL PROBLEM DEFINITION

Dynamical state-space model of a permanent magnet brushed DC linear motor can be expressed as [17]

$$\frac{di_a(t)}{dt} = -\frac{R}{L}i_a(t) - \frac{K}{L}v(t) - \frac{1}{L}e(t) \tag{1}$$

$$\frac{dv(t)}{dt} = \frac{K}{M}i_a(t) - \frac{\alpha}{M}v(t) \tag{2}$$

where $i_a(t)$, armature current (A), and $v(t)$, armature speed (m/sec), are the state variables, $e(t)$, armature voltage (V), is the control input signal. The parameters are R, coils resistance (Ω), L, coil inductance (H), α, viscous friction coeeficient, K, force coefficient (N/A), and M, mass of the moving part (kg). In vector-matrix form, the system model can also be expressed as

$$\begin{bmatrix} \frac{di_a(t)}{dt} \\ \frac{dv(t)}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & -\frac{K}{L} \\ \frac{K}{M} & -\frac{\alpha}{M} \end{bmatrix} \begin{bmatrix} i_a(t) \\ v(t) \end{bmatrix} + \begin{bmatrix} -\frac{1}{L} \\ 0 \end{bmatrix} e(t) \tag{3}$$

$$y = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_a(t) \\ v(t) \end{bmatrix} \tag{4}$$

where linear model is considered under no-load condition. An experimental study to determine the exact values of the parameters in the dynamical model given above has been presented in [24]. Due to lack of space, details of the determination process have not been presented here. By using the experimental values given in [24], the model given above can be represented as

$$\begin{bmatrix} \frac{di_a(t)}{dt} \\ \frac{dv(t)}{dt} \end{bmatrix} = \begin{bmatrix} -391.11 & -4444.44 \\ 12.60 & -4.46 \end{bmatrix} \begin{bmatrix} i_a(t) \\ v(t) \end{bmatrix} + \begin{bmatrix} -22.22 \\ 0 \end{bmatrix} e(t) \tag{5}$$

$$y = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_a(t) \\ v(t) \end{bmatrix} \tag{6}$$

since the parameter values are R=17.6 Ω, L=45 mH, K=200 N/A, M=15.88 kg, =200 N/A, and α=70.91. The eigenvalues of the system matrix given in Eq. (5) are $\lambda_{1,2}=-2\pm j1.36$. This necessarily means that the system is inherently stable since its eigenvalues have negative reals parts. Even so, the system should be controlled to ensure that the system satisfies a predefined performance specifications. So the first control problem can be defined as "*for the system given in Eqs. 5&6, design the control input signal, $e(t)$, to ensure that the system has 0.1 second settling time and 10% percent overshoot for step input*".

Note that one of the state variables is the speed of the motor. Generally speaking, speed of a DC motor is measured by taking the time derivative of position information taking by using a position sensor. But numerical derivation adds noise to the system. This may lead chattering, one of the most important problems in electromechanical system. For this reason, after presenting the design of a controller for the problem defined above, an observer design for the estimation of the speed of the motor to avoid chattering problem is also presented. Instead of defining it as a control problem, an observation problem can be defined as follows: "*for the system given in Eqs. 5&6, design an observer with observation performance of 0.02 second settling time and %20 percent overshoot for step input".* In the observer design, it will be assumed that the both state variables are not available for measurement. The following chapter provides a control design algorithm step-by-step for the defined control problem. Full state feedback is used in the controller design. Chapter IV shows the design of a Luenberger Observer for the observation problem defined above. Simulation results of the controller and observer have also been provided to show the performance and feasiblity of the designed controller and observer.

III. CONTROLLER DESIGN

To be able to design a state-feedback controller for the system given in Eqs. 5&6, first the controllability of the system must be checked. The controllability matrix,

$$\boldsymbol{P_C} = [\boldsymbol{B}\ \boldsymbol{AB}] = \begin{bmatrix} -22.22 & 8690.5 \\ 0 & -279.97 \end{bmatrix} \tag{7}$$

is full rank since its determinant equals 6221. So the system is controllable and a state-feedback controller can be designed for it. Since the system order is 2, then the state feedback controller will have the form

$$e(t) = u(t) = -\boldsymbol{Kx(t)} = [K_1 \quad K_2]\begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} = -K_1x_1(t) - K_2x_2(t) = -K_1i_a(t) - K_2v(t) \tag{8}$$

where $u(t)$ is the control input signal, and $\boldsymbol{K} = [K_1 \quad K_2]$ is the controller gain vector. To find the values of the control gains, K_1 and K_2, a standard derivation for the linear time-invariant systems can be used. Consider the general form of the state equation for a linear time-invariant system:

$$\dot{\boldsymbol{x}} = \boldsymbol{Ax} + \boldsymbol{B}u \tag{9}$$

If the control input signal, $u(t)$, is designed as in Eq. (8), i.e., $u(t) = -\boldsymbol{Kx(t)}$, then the final form of the state equation will be

$$\dot{\boldsymbol{x}} = (\boldsymbol{A} - \boldsymbol{BK})\boldsymbol{x} \tag{10}$$

To be able to say that the vector differential equation given in Eq. (10) is bounded, i.e., stable, the necessary and sufficient condition is the eigenvalues of the newly-formed system matrix, $(\boldsymbol{A} - \boldsymbol{BK})$, must have negative real parts [25]. Investigating this matrix yields

$$\boldsymbol{A} - \boldsymbol{BK} = \begin{bmatrix} 22.22K_1 - 391.11 & 22.22K_2 - 4444.44 \\ 12.6 & -4.46 \end{bmatrix} \tag{11}$$

and its eigenvalues are

$$\det(s\boldsymbol{I} - (\boldsymbol{A} - \boldsymbol{BK})) = s^2 + (395.57 - 22.22K_1)s + (57744 - 280K_2 - 99K_1) \tag{12}$$

To design the control gains, the general form of the characteristic equation of second-order systems with pre-defined control objective given in Chapter II can be used. "*0.1 second settling time and 10% percent overshoot*" yields a damping ratio of $\varphi = 0.591$ and a natural frequency of $\omega_n = 67.68$ rad/sec. So the characteristic equaiton will be

$$s^2 + 2\varphi\omega_n s + \omega_n^2 = s^2 + 80s + 4578.40 \tag{13}$$

By considering Eqs. (12) and (13) together, the values of the control gains are found as $K_1 = 14.2$ and $K_2 = 184.84$. So the control gain matrix will be in the form of

$$\boldsymbol{K} = [K_1 \quad K_2] = [14.2 \quad 184.84] \tag{14}$$

and the control input signal, which is the voltage to be applied to the motor, will be in the form of

$$e(t) = -K_1i_a(t) - K_2v(t) = -14.20i_a(t) - 184.84v(t) \tag{15}$$

Numerical simulation of the designed controller will be given in Section V.

IV. OBSERVER DESIGN

For some type of applications, the state variables may not be available for measurements, or, even if they are available for measurement, measuring some state variable may add considerable noise to the system. This noise may lead to chattering, which is one of the most important problems in electromechanical systems. For the system considered in this study, one of the state variables is speed of the moving part, the armature. The easiest way to measure it is to measure the position of the armature by using some sensors and then taking time derivative of position information. But numerical derivation generally adds noise to the system. This may lead to fluctuation in control input signal, which is the voltage to be applied to the motor. So an observer to estimate the dynamic values of the state variables may be needed. In this study, a full-state uncertainty will be considered and a Luenberger Observer [25] will be designed to estimate the state variables.

To be able to design an observer for the system given in Eqs. 5&6, first the observability of the system must be checked. The observability matrix,

$$P_o = [\boldsymbol{C}\ \boldsymbol{CA}]^T = \begin{bmatrix} 0 & 1 \\ -12.60 & -4.46 \end{bmatrix} \tag{16}$$

is full rank since its determinant equals -12.60. So the system is observable and an observer can be designed for it. General form of the Luenberger Observer for linear time-invariant systems is

$$\frac{d}{dt}\hat{\boldsymbol{x}} = \boldsymbol{A}\hat{\boldsymbol{x}} + \boldsymbol{B}u + \boldsymbol{L}(\boldsymbol{y} - \boldsymbol{C}\hat{\boldsymbol{x}}) \tag{17}$$

where $\hat{\boldsymbol{x}}$ is estimation of state vector, $\boldsymbol{x}$, and $\boldsymbol{L}$ is the observer gain matrix in the form of $\boldsymbol{L} = [L_1 \quad L_2]^T$ since the system is second-order. To quantify the observation performance of the observer to be designed, an observation error signal can be defined as

$$\boldsymbol{e} = \boldsymbol{x} - \hat{\boldsymbol{x}} \tag{18}$$

Note that if the error signal given in Eq. (18) goes to zero, this necessarily means that $\hat{\boldsymbol{x}} \rightarrow \boldsymbol{x}$, i.e., estimated values of the state variables go to their real values. To ensure that it goes to zero, its dynamics can be investigated as

$$\dot{\boldsymbol{e}} = \dot{\boldsymbol{x}} - \frac{d}{dt}\hat{\boldsymbol{x}} \tag{19}$$

and if Eq. (17) is substituted into Eq. (18), it results in

$$\dot{\boldsymbol{e}} = (\boldsymbol{A} - \boldsymbol{LC})\boldsymbol{e} \tag{20}$$

where the output equation of a single-input single-output system, $y = \boldsymbol{Cx}$, has been subtituted into Eq. (19) also. To be able to say that the vector differential equation given in Eq. (19) is bounded, i.e., stable, the necessary and sufficient condition is the eigenvalues of the newly-formed system matrix, $(\boldsymbol{A} - \boldsymbol{LC})$, must have negative real parts [25]. Investigating this matrix yields

$$\boldsymbol{A} - \boldsymbol{LC} = \begin{bmatrix} -391.11 & -L_1 - 4444.44 \\ 12.6 & -L_2 - 4.46 \end{bmatrix} \tag{21}$$

and its eigenvalues are

$$\det(s\boldsymbol{I} - (\boldsymbol{A} - \boldsymbol{LC})) = s^2 + (395.57 + L_2)s + (57744 + 391.11L_2 + 4.46L_1) \tag{22}$$

To design the observer gains, the general form of the characteristic equation of second-order systems with pre-defined control objective given in Chapter II can be used. "*0.02 second settling time and %20 percent overshoot*" yields a damping ratio of $\varphi = 0.455$ and a natural frequency of $\omega_n = 438.64$ rad/sec. So the characteristic equaiton will be

$$s^2 + 2\varphi\omega_n s + \omega_n^2 = s^2 + 400s + 192410 \tag{23}$$

By considering Eqs. (22) and (23) together, the values of the observer gains are found as $L_1 = 29985$ and $L_2 = 4.43$. So the observer gain matrix will be in the form of

$$\boldsymbol{L} = [L_1 \quad L_2]^T = [29985 \quad 4.43]^T \tag{24}$$

Numerical simulation of the designed observer will be given in Section V.

V. NUMERICAL SIMULATION

All the numerical simulations are done by using MATLAB/Simulink environment. Values of the controller and observser gains are set to the values found in Sections III and IV, respectively. All the system parameter values are set to the values as in [24], also given in Section II. Figure 5 shows the step response of the designed closed-loop system. As shown in the figure, percent overshoot is 10%, as predescribed, and settling time is 0.0876, less than predescribed 0.1, due to rounding errors.

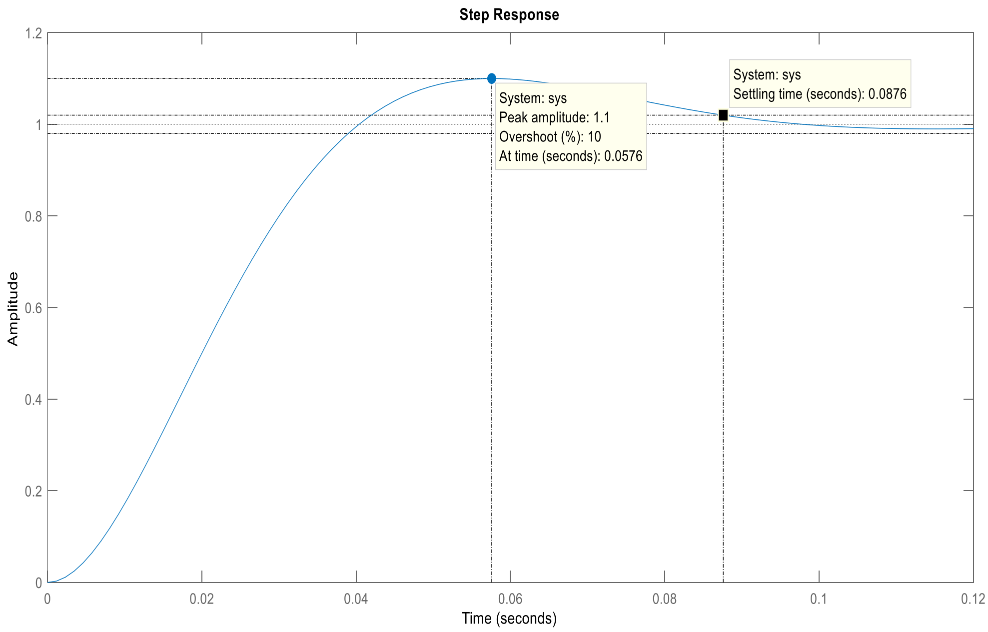

Figure 5. *Step response of the designed closed-loop system*

Figure 6 shows the step response of the designed observer dynamics. As designed, the percent overshoot is 20%. Settling time is 0.019, less than predescribed 0.02 due to rounding errors. Note that its final value is 1, which means the designed observer guarantees that it estimates the unmeasurable state variables with zero observation error while time goes to infinity, with a settling time of 0.019 second and a percent overshoot of 20%. It is worthy to point out that these performance criterion, percent overshoot of 20% and settling time of 0.02 second, is quite forcing values for an electromechanical system, which leads high observer gain values. One can also choose performance values as less forcing values, which leads smaller observer gain values.

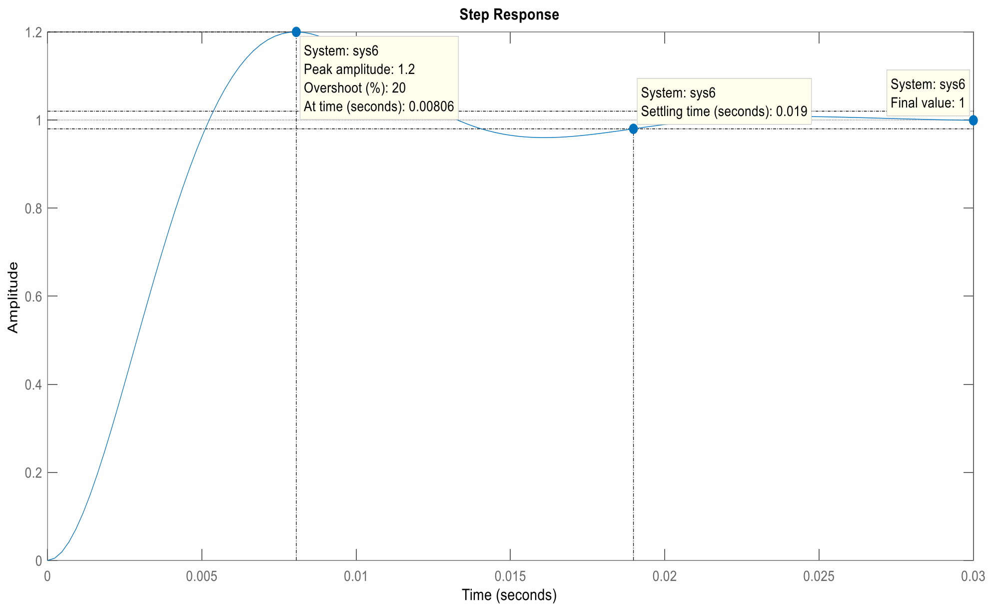

Figure 6. *Step response of the designed closed-loop observer*

VI. CONCLUSION

A state-feedback controller and full-state observer have been designed for a novel permanent magnet DC linear motor. Designed state-feedback controller guarantees that the closed-loop system has specifications of 0.1 second settling time and 10% percent overshoot. In addition, the designed observer guarantees that observation error will converge to zero while time goes to infinity. In this way, a controller design will be possible even if the state variables are not available for measurement. The designed Luenberger Observer also has performance specifications of 0.02 settling time and 20% percent overshoot, which are very challenging and leads to large values of observer gains. Numerical simulation results obtained by using MATLAB/Simulink environment proves the performance and feasibility of both the controller and observer.

Some future prospects should also be worthy to point out. Designed and simulated controller can be implemented by using a proper software and hardware combination. Such an experiment will add value to the proof of performance and feasibility of the controller designed in this study. Some other types of feedback or feedforward control methods could also be considered.

In addition, the observer design can also be implemented to show the real-time performance and feasibility of the estimation scheme introduced in this study. Even if the Luenberger Observer is the most common and well-known observer type for a second-order system, some alternative observation schemes could also be considered.

Note that the dynamical model given in Eqs. (1) and (2) is linear. Nonlinear model of the permanent magnet DC linear motor introduced in this study can also be used to design some nonlinear controllers with better performance. Design of such a nonlinear controller is the authors' current interest. This will also lead to need of designing a nonlinear state observer for this system. So the nonlinear observer design and implementation is another future prospect.

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