

# Sensorless load and position estimation in linear reluctance actuator

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**Abstract:** Sensorless load and position estimation of linear reluctance actuator is investigated in this paper. Due to wide application of these actuators in several industrial automation systems, sensorless techniques are significant to decrease the cost of the system and increase the reliability in the closed-loop control systems. In this paper, based on dynamic model of the actuator and the characteristics of its subsystems, the possibility of sensorless estimation of mechanical parameters is explored. Considering nonlinear behavior of magnetic subsystem, the position of the plunger could be estimated based on the winding inductance and the excitation current value. Then, the amount of load force could be determined based on current value and estimated position. Laboratory measurements of the actuator's characteristics assist in increasing the accuracy of estimation besides dynamic modeling.

**Keywords:** reluctance actuator, sensorless, position, force, estimation

**Classification:** Electronic instrumentation and control

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## 1 Introduction

Linear reluctance actuators have many applications in several parts of industries due to their simple construction, low prime cost, and high ruggedness. There are two types of linear reluctance actuators, known as on-off and proportional [1]. Since closed-loop position control in force operators with high accuracy is so common, the entire plunger trajectory in proportional actuator is controlled. Transfer function in proportional actuators is more linear than on-off actuators but the design in proportional actuators is much more complex. Moreover, proportional actuators require position sensor, thus they are more expensive [2]. Converting an on-off actuator to a proportional one employing power electronic converters and external sensors with operating range of below 10 mm has been investigated in [3]. In order to increase reliability and decrease total system's cost, sensorless methods are introduced and are being developed in various automation systems. These methods generally employ electrical parameters to estimate mechanical parameters, thus external sensors and other peripherals could be preserved. Several methods are proposed to estimate the position of the linear actuators in different researches. Some researches like [4] have employed state observers like "slide mode observer" to estimate the position of the plunger. These methods are more complex in computation. Other researchers have tried to use electromechanical characteristic and electromotive equations to estimate the position. [5] Used auxiliary coil, attached to the main windings to reconstruct flux and inductance for estimation. In [6], a method based on measuring the back EMF, is described to determine the plunger position by adding small mechanical vibration. Since plunger's permanent motion is not desirable, this method has limitations in many applications. In [3, 7], plunger position estimation has been carried out by measuring the time slope of current and the relation of this quantity with inductance and position. Additionally, inductance measurement is performed by injecting the sine wave voltage into the winding of the motor. The inductance is measured with phase shift [8] or amplitude [9, 10] of the generated current. In the mentioned researches, there is no significant study about position estimation either on load estimation or load effect. In this paper, position estimation of the plunger in the linear reluctance actuator is studied with the approach of load effects. However, the load estimation is taken into consideration in this paper. Experimental

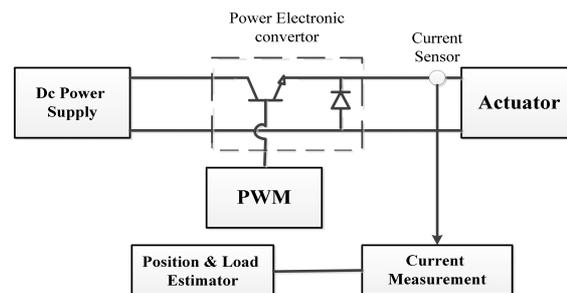


Fig. 1. Basics of position and load estimation in PWM drive of actuator

study of the actuator has made the theoretical claims confirmed.

## 2 System's model

The dynamic equations of the actuator could be divided into electrical, mechanical, and magnetic subsystems. Fig. 2 illustrates these main subsystems and their relationships. According to this diagram, supply voltage and load force are the system inputs. Electrical and magnetic subsystems connect with each other through  $\lambda$  and  $i$  whereas magnetic block is in relation with mechanical one through  $F_{mag}$  and  $x$ . In this paper, mechanical and electrical subsystems are studied to estimate the position of the plunger ( $x$ ) and load force ( $F_{Load}$ ). The electrical equation could be defined as:

$$V = Ri + N \frac{d\phi}{dt} \quad (1)$$

In Eq. (1),  $V$  is the actuator's voltage,  $R$  is the winding resistance,  $N$  is the number of the winding turns, and  $\phi$  is the flux inside the winding. Considering  $\lambda = N \cdot \phi$ , Eq. (1) would be rewritten as the following:

$$V = Ri + \frac{d\lambda}{dt} \quad (2)$$

$\lambda$  is the flux linkage and its value is determined by magnetic analysis at any plunger position and anytime. Note that  $V$  is the instantaneous voltage of the winding, therefore when the actuator is modeled by power electronic convertors with PWM, it is modeled with  $V = 0$  at off periods, due to the presence of Freewheeling diode. By assuming vertical position for the actuator, in order to define the equation of the mechanical subsystem, the applied forces to the moving part of the system are expressed by: Plunger Weight, Friction Force, Magnetic Force and Load Force. Therefore, dynamic equation of the mechanical subsystem is defined as:

$$F_{mag} - W_p - F_f - F_{load} = m_p \ddot{x} \quad (3)$$

In Eq. (3),  $F_{mag}$  is the magnetic force,  $W_p$  is the plunger weight,  $F_f$  is the friction force and  $m_p$  is the mass of the plunger. Since the linear actuator is in vertical position and the vertical force is not defined, the friction force value of the actuator is in proportion with the plunger velocity [11].

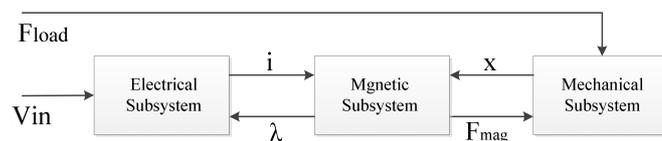


Fig. 2. Block diagram of linear actuator

## 3 Inductance and position

In the simplest status, the actuator could be assumed as a resistor in series with an inductance. The amount of inductance can vary in different situations

accompanied with other parameters. For more details, Eq. (2) could be rewritten as:

$$V = Ri + \frac{\partial \lambda}{\partial i} \cdot \frac{di}{dt} + \frac{\partial \lambda}{\partial x} \cdot \frac{dx}{dt} \quad (4)$$

In Eq. (4), the first statement is the resistance voltage and depends to the resistance of winding that can vary with temperature, frequency and etc. This parameter assumed constant in the situation of this study. Second term is the inductance voltage and depends to magnetic working point and also the time derivative of current. Due to the flux linkage of actuator is a function of plunger position and winding current [2], the second term of voltage depends to  $x$  and  $i$ . The third term of (4) is back EMF (Electromotive force) and depends to the working point of system and velocity of the plunger. This voltage induced due to reluctance change in the magnetic subsystem by plunger movement. Note that in the steady states or low-velocity movement of the plunger, this term have low value and could be omitted. In [7], the effect of omitting this term on the accuracy of estimation has been discussed. At the mentioned condition, Eq. (4) would be rewritten as:

$$V = Ri + \frac{\partial \lambda}{\partial i} \cdot \frac{di}{dt} \quad (5)$$

This equation is being used to measure the amount of working point inductance and to estimate the position of plunger. There are two strategies to measure the inductance:

### 3.1 Current's slope measurement

This method is based on voltage's inherent ripple and its resultant change rate of the current. In this case, the amount of  $di/dt$  should be sufficiently large and measureable. Thus, PWM frequency should be small enough without any plunger vibration. Eq. (5) results in:

$$L(x, i) = \frac{\partial \lambda}{\partial i} = \frac{V - Ri}{di/dt} \quad (6)$$

In [7], a special circuit is proposed for measuring current' slope. But this method requires high frequency synchronization and also it is sensitive to noise. However, the amount of inductance could be calculated approximately by integrating over the numerator and denominator of the fraction in (6), to decrease the effect of noise. Note that the integral should be determined at one of "on" or "off" periods of the PWM.

$$L(x, i) = \frac{\int_{PWM-on} (V - Ri).dt}{\Delta i_{PWM-on}} = \frac{\Delta \lambda_{PWM-on}}{\Delta i_{PWM-on}} \quad (7)$$

### 3.2 Scan signal injection

In this method, high frequency PWM is employed to modulate and inject a sine wave voltage into the winding, in addition to the excitation voltage. The current response of injected voltage could be detected as phase shifting or

amplitude. Regarding high frequencies in the produced voltage and assuming the voltage like Eq. (8), leads to Eq. (9) for current in the steady state.

$$V_{in} = V_d + V_m \sin(\omega t) \quad (8)$$

$$i = I_d + I_m \sin(\omega t + \varphi) \quad (9)$$

By regarding EMF term and using Eq. (8) in Eq. (5) we have:

$$V_d + V_m \sin(\omega t) = iR + \frac{\partial \lambda}{\partial i} \cdot \frac{di}{dt} \quad (10)$$

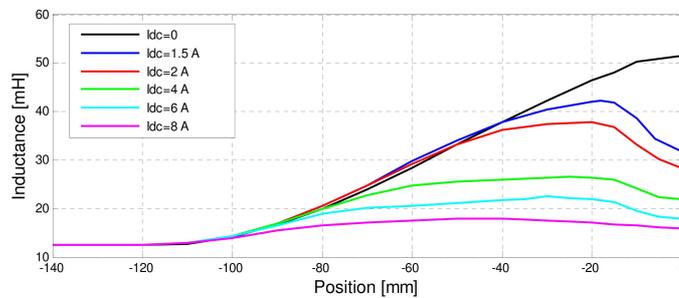
At the steady state situation we can write:

$$I_d = \frac{V_d}{R} \quad (11)$$

$$I_m = \frac{V_m}{\sqrt{R^2 + (\omega \cdot \frac{\partial \lambda}{\partial i})^2}} \quad (12)$$

$$\varphi = \tan^{-1} \left( \frac{\omega \cdot \frac{\partial \lambda}{\partial i}}{R} \right) \quad (13)$$

Compared to the first method, this technique has less noise sensitivity due to higher switching frequency. The frequency of scan signal in this method should be significantly lower than switching frequency. Fig. 3 illustrates the experimental measurements of the motor's inductance in different positions and for various excitation currents. It is measured by injecting 500 Hz ac voltage into excitation dc supply with 20 kHz PWM technique. As shown in this figure, the inductance apart from the plunger position is dependent on the actuator's current. Moreover, due to magnetic saturation, the values of inductance decrease by increasing the current after a critical point. This phenomenon restricts the estimation range. Other limitation is decreasing the sensitivity of inductance to the position for large values of excitation current that could decrease the accuracy of estimation. The estimation system should be able to measure the amplitude of ac component (resulting inductance) and dc component of the current and then calculate the position, based on Fig. 3 values, with proper interpolation.



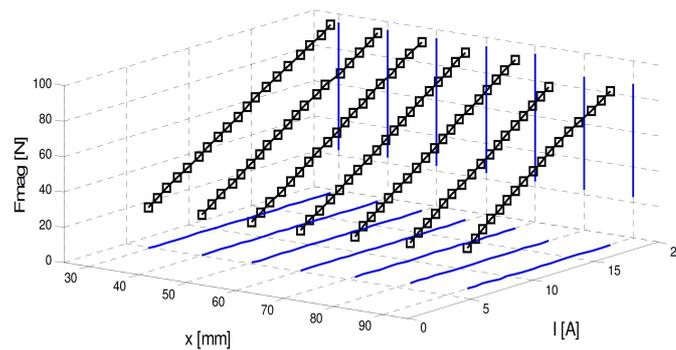
**Fig. 3.** Experimental measurements of the actuator's inductance, 500 Hz scan signal injection

#### 4 Excitation current and load

According to Eq. (3), in the balance state of forces or in low values of the plunger velocity, we have:

$$F_{mag} = W_p + F_{load} \quad (14)$$

The amount of  $W_p$  is constant. In addition,  $F_{mag}$  is the function of excitation current and plunger position [2]. The amount of magnetic force could be achieved from magnetic model of the system or laboratory measurements. In this case, we can estimate the value of load force according to the estimated position and excitation current for inertia or low-speed movements. Fig. 4 shows the magnetic force values in the experimental study of the system. As shown in this figure and based on the magnetic model of system [2], the amount of magnetic force depends on the current more than the position. As a result, to estimate load force and plunger position, the first step is to determine the position based on ac component (results inductance) and dc component of current. The second step is to estimate the load force based on Eq. (14) and Fig. 4. Using this technique, results in sensorless estimation of load and position. However, it has some considerations that are out of this paper's scope.



**Fig. 4.** Magnetic force in several positions and different currents, Experimental measurement

#### 5 Conclusion

In this paper, sensorless position and load estimation in the linear reluctance actuator are studied. By exploring dynamic model of the actuator, the basic equations of electrical and mechanical subsystems are used to extract the principles of position and load estimation. Due to nonlinear behavior of actuator and its magnetic saturation, the inductance of winding, apart from the position, is a function of excitation current. Consequently, ac and dc components of current should be taken into consideration in order to estimate the position. Therefore, after the position is estimated, the value of load force could be determined in low-velocity movements, based on the excitation current and estimated position. The experimental measurements' data is introduced to help the proposed theoretical methods to estimate plunger position and load force.