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EFFECT OF FORCE STAGES APPROACH FOR SENSOR LESS LINEAR DC MOTOR POSITIONING SYSTEM

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RINGKASAN : *Motor linear telah mula mendapat perhatian sebagai pemacu gerakan linear di industri dan automasi perkilangan. Perkembangan ini dimangkinkan oleh kelebihan yang ditawarkan oleh motor linear seperti saiz dan rekabentuk yang fleksibel, serta menawarkan prestasi tinggi untuk aplikasi-aplikasi gerakan linear. Bagaimanapun, halangan utama kepada pereka sistem untuk menggunakannya dalam aplikasi mereka ialah kos bagi keseluruhan pakej motor linear. Umumnya, motor linear lebih mahal berbanding saingannya disebabkan oleh teknologi penderia bagi sistem penetapan kedudukan. Bagi litar pemandu motor linear yang biasa, penderia kedudukan biasanya digunakan bagi menyediakan isyarat suap balik kedudukan kepada litar pengawal. Walaubagaimanapun, bagi aplikasi yang tidak memerlukan ketepatan kedudukan seperti pencengkam robot, penderia kedudukan yang mahal dan berketepatan tinggi adalah tidak diperlukan. Tanpa penderia kedudukan ini di dalam sistem akan dapat mengurangkan kos keseluruhan pakejnya. Kajian ini mencadangkan satu sistem penetapan kedudukan tanpa penderia bagi motor linear DC (LDM). Idea yang digunakan untuk mengawal kedudukan LDM adalah dengan mengawal jumlah arus yang dibekalkan kepada motor menggunakan teknik manipulasi isyarat denyut modulasi lebar (PWM). Beberapa variasi isyarat PWM digunakan untuk memacu motor tersebut iaitu satu fasa, dua fasa, tiga fasa dan empat fasa. Variasi isyarat PWM ini dihasilkan dengan menggabungkan beberapa nilai kitar kerja yang berbeza dan digabungkan di dalam satu isyarat PWM. Satu model matematik bagi LDM yang dibina telah diterbitkan berasaskan kepada teori ayunan paksa dengan redaman bagi sistem beban-pegas. Persamaan gerakan bagi LDM ini kemudiannya disimulasikan menggunakan perisian Matlab. Perbandingan yang dibuat ke atas hasil simulasi dan eksperimen sebenar menunjukkan keputusan yang hampir sama. Sambutan masa sistem berdasarkan simulasi telah diteliti bagi memperbaiki kualiti sambutan sementara sistem.*

ABSTRACT : Linear motor has gained popularity as linear motion drive in industry and factory automation. These developments were encouraged by the advantages offered by linear motors such as flexibility in size and design, and deliver high performance for applications requiring linear motion. However, the main constraint for system designer to consider linear motors in their application is the cost for every complete package of linear motor. Generally, linear motors are more expensive than its counterparts due to the sensory technologies used for positioning system. For typical linear motor driver, a positioning sensor is usually attached to the motor which provide feedback positioning signal to the controller. For some applications, where positioning is not too critical such as robot end gripper, the high precision and expensive positioning sensor is not necessary. Removing this sensor from the system reduce the overall system cost. This research propose a sensor less positioning system for linear DC motor (LDM). The ideas to control the position of the LDM are by controlling the current supplied to the motor by using manipulating technique of Pulse Width Modulation (PWM) signal. A few variant patterns of PWM signal are used to drive the motor which is single stage, dual stage, triple stage and quadruple stage. The variant patterns of PWM signal were created by combining multiple values of duty cycle running in a single PWM signal. A mathematical model for constructed LDM has been derived based on damped force oscillation of mass spring system theory. The equation of motion for LDM is then simulated using Matlab software. The time response of the system based on simulation results has been studied and proper adjustment to control parameters has been made to improve the rise time, overshoot percentage and steady state error.

KEYWORDS : Linear DC Motor, PWM signal, duty cycle, single stage, dual stage, triple stage, quadruple stage

INTRODUCTION

Linear DC Motors (LDM) produce linear motion without using any intermediate mechanical conversion devices. Unlike conventional rotary motor, the absence of intermediate mechanical transmission devices such as gears, belts and motor coupling eliminates backlash and compliance, reducing friction and wear, thus increase motor efficiency (Lee *et al,* 2000). The construction of a linear motor does not need any extra tools such as screw or gear mounted on it. Besides its simple construction, linear motor offers a low production cost with highest thrust produced. Also, the thrust produced by a linear motor can be used directly without any auxiliary procedures. For motor positioning purposes, digital controllers require position sensors to detect the position of the motor and send feedback signal to the controllers. Typical position sensor for linear motor application includes linear encoders and incremental encoders. Linear encoders measure the relative position of the moving and stationary parts of the drive while incremental encoders measure the changes of position rather than absolute position. These advance sensory technologies used in close loop linear motor system especially for high accuracy performance can cause an increase in overall cost and complexity of the system (Norhisam *et al,* 2006). However, for simple and low cost applications which do not require precise positioning, an open loop system can be an alternative. In this paper, combination of spring and force produced by LDM was used to determine the position of LDM. Manipulation of PWM's duty cycle technique was used to produce LDM force and at the same time give an external force to the spring. The spring will be stretched at certain length until the value of external force is equal to the force absorbed by the spring. The length of stretched spring will then determine the position of LDM. By using this system, the desired position can be achieved accurately similar to that using close loop system attached with sensor. Besides reducing the system complexity, it will reduce overall cost as much as 10 times compared to close loop system. In this paper, effect of force stages to the performance of sensor less LDM will be studied.

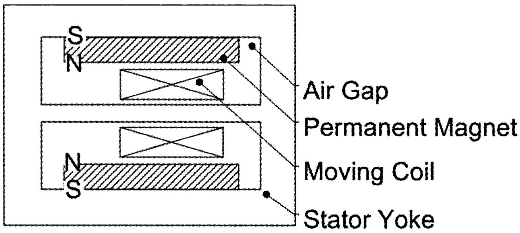
BASIC PRINCIPLE OF SENSOR LESS LINEAR DC MOTOR

Basic structure of linear dc motor (Norhisam *et al,* 2004) is shown in Figure 1 (a). It consists of a stator yoke, a moving coil and a couple of permanent magnets with similar pole facing each other. The moving coil is able to move either in forward or reverse direction depending on the polarity of the current supply.

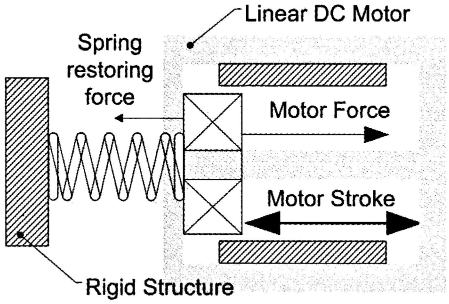
The basic principle of thrust in LDM is derived from basic *iBl* laws or known as Ampere's law. Thrust in the moving coil can be expressed as equation (1) :

$$F_m = N_c I B_g l_c \tag{1}$$

Where, F_m is thrust in (N), N_c is number of coil turns, I is current supplied to the coil in (A), B_g is flux density in the gap in (T) and l_c, is length of the coil in gap in (m).



(a) Basic structure of LDM



(b) LDM with positioning spring

Figure 1. *Structure of LDM*

The thrust constant of the LDM is dependent on the value of N_c, B_g and l_c, and these parameters are fixed when the motor was designed. Therefore, the force produced by the motor can be controlled by controlling the amount of current supplied to the coil. Assuming

$$K_f = N_c B_g l_c \tag{2}$$

$$F_m = K_f I \tag{3}$$

Thus, it implies that the force produced by the motor is proportional to the current supplied. High values of forces will be produced if high values of current are supplied to the coil.

A basic model of LDM based on design in Norhisam *et al.* (2004) will be constructed for experimental purposes. A modification is made to the motor by connecting a mechanical spring to the moving coil as shown in Figure 1 (b). The purpose of this mechanical spring is to absorb the force produced by the motor. Once the force produced by the motor is equal to the force absorbed by the spring, the moving coil will stop at some distance. The displacement of the spring will then be used to determine the position of the motor (Norhisam *et al*, 2006). Due to the harmonic oscillation produced in mass-spring system, the position of the motor oscillates before reaching the final desired position. In order to eliminate the harmonic oscillation effect, a few variant patterns of PWM signal are used to drive the motor. These variant patterns are single stage, dual stage, triple stage and quadruple stage. The variant patterns of PWM signal were created by combining multiple values of duty cycle running in a single PWM signal.

MODELLING OF SENSOR LESS LINEAR DC MOTOR

LDM System Modeling

The purpose of system modeling is to obtain an accurate mathematical equation of motion for the LDM. This equation describes the position or displacement of the LDM after certain input

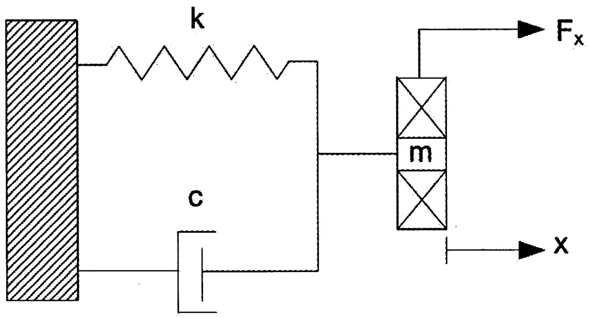


Figure 2. *Free body diagram of mass spring system*

(forces) applied to the system. In order to describe the motion of LDM, the study of mass spring system is necessary since it has similar concept. The spring-mass system can be thought of as representing a single mode of vibration in a real system (Kao *et al*, 2006), whose natural frequency and damping coefficient coincide within the system. A mass spring system consists of a simple mass m that is connected to a mechanical spring with a known stiffness k and a dashpot damper c from a fixed support. A LDM system can be represented as mass spring system with moving coil as the mass, the spring and the surface friction as dashpot damper.

Consider a free body diagram of mass spring system in Figure 2. By using Newton's second law of motion, the force $F_m(t)$ applied to a mass equals its mass m times its acceleration a. When a mass m connected to a spring, it will be displaced from the equilibrium position to a new position x. According to Hooke's law for ideal springs, the compression force $F_s(t)$ applied to a spring is equal to the spring constant k times the displacement x (Kao *et al,* 2006).

$$F_m(t) = ma \qquad (1) \qquad\qquad F_s(t) = -kx \qquad (2)$$

Newton's third law says that every force has an equal and opposite force. Thus

$$F_m(t) = F_s(t)$$

$$m\frac{d^2x}{dt^2} + kx(t) = 0 \qquad (3)$$

In addition, all mechanical motions are damped to some degree of friction force that resists the motion. It is proportional to the velocity of the mass. By considering these friction forces $cx(t)$ acting on the mass and external forces F_x acting on the system, equation (3) of motion becomes

$$m\frac{d^2x}{dt^2} + c\frac{dx}{dt} + kx(t) = F_x(t) \qquad (4)$$

where m is the mass of the system, k is the stiffness of the spring, and c is the viscous damping coefficient. Taking Laplace Transform on both sides of equation, transfer function of the system is

$$G(s) = \frac{X(s)}{F_x(s)} = \frac{1}{ms^2 + cs + k} \tag{5}$$

Using partial fractions and inverse Laplace tranforms to solve equation above, the equation of $g(t)$ will be as below

$$\begin{aligned} g(t) &= L^{-1}G(s) \\ &= \frac{1}{k}\left[1 - e^{-at}\cos bt - \frac{a}{b}e^{-at}\sin bt\right] \end{aligned} \tag{6}$$

Where $a = \frac{c}{2m}$ and $b = \sqrt{k/m - \left(c/2m\right)^2}$

Single Stage Force Approach

The easiest way to control the position of the motor is by using a single pattern of PWM signal. This approach uses only one value of PWM's duty cycle to energize the coil (Norhisam *et al*, 2006). The value of duty cycle depends on the desired displacement of the motor. In other words, the LDM is given by single constant value of force as shown in Figure 3. The force should be applied until the desired displacement is achieved.

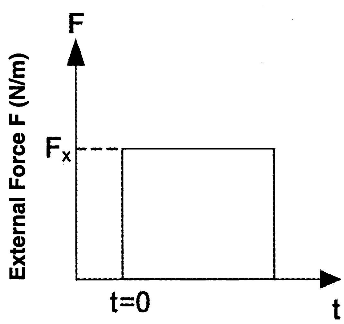


Figure 3. *Single stage PWM driving signal*

Thus, the solution for equation of motion becomes

$$G(s) = \frac{X(s)}{F_X(s)}$$

$$X(s) = G(s)\,F_X(s)$$

Taking inverse Laplace on both sides

$$x(t) = L^{-1} G(s)\,F_X(s)$$

$$x(t) = \frac{f_X}{k}\left[1 - e^{-at}\cos bt - \frac{a}{b}e^{-at}\sin bt\right] \quad (7)$$

Dual Stage Force Approach

The main objective for dual stage approach is to improve the rise time of single stage approach. Dual stage approach employs two different values of duty cycle in a single PWM signal. The intention of first duty cycle is to reduce the rise time of the transient response while the second duty cycle is used to maintain the position of the motor at desired position (Norhisam *et al*, 2006). Dual stage PWM driving signal is shown in Figure 4. In order to reduce the rise time of the response, the first duty cycle should have the highest possible value.

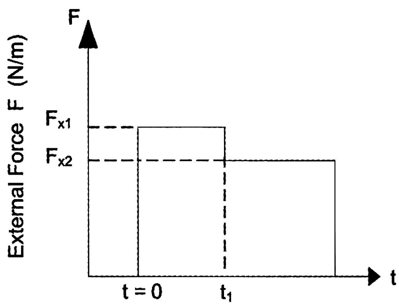


***Figure 4.** Dual stage PWM driving signal*

Consider external forces acting on the mass spring system as shown in Figure 4. The force is non periodic function consisting of two different values of forces, F_{x1} and F_{x2} with t_1 as time duration for the first force deployed. The non periodic function for external forces can be written as follows :

$$Fx(t) = \begin{Bmatrix} Fx1 & 0 < t < t_1 \\ Fx2 & t > t_1 \end{Bmatrix} \quad (8)$$

Taking Laplace Integral and Laplace Transform of the driving force using t-shifting theorem :

$$F_x(s) \;=\; \frac{F_{x1}}{s} - \frac{(F_{x1} - F_{x2})}{s}\, e^{-t_1 s}$$

Finally, the solution for equation of motion for LDM in dual stage approach is given by :

$$x(t) \;=\; L^{-1} G(s)\, F_x(s)$$

$$x(t) \;=\; \frac{F_{x1}}{k}\left[1 - e^{-at}\cos bt - \frac{a}{b} e^{-at}\sin bt\right]$$

$$-\frac{(F_{x1} - F_{x2})}{k}\left[1 - e^{-a(t-t_1)}\cos b(t-t_1) - \frac{a}{b} e^{-a(t-t_1)}\sin b(t-t_1)\right] \qquad (9)$$

Triple stage Force Approach

If three different external forces F_{x1}, F_{x2} and F_{x3} act on the system as shown in Figure 5, it is called triple stage force approach. It uses three different values of PWM duty cycle to produce three different values of external force. Triple force approach was used to eliminate the overshot produced by dual stage force approach while maintaining fast rise time.

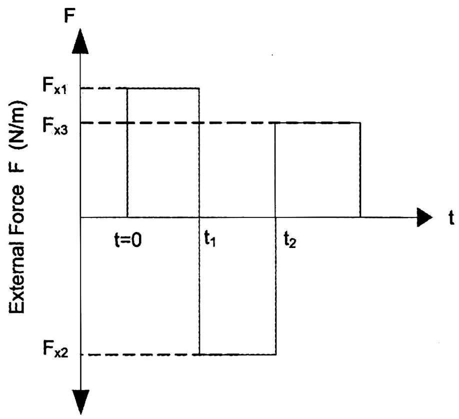


Figure 5. *Dual stage PWM driving signal*

The non periodic function for external forces can be written as follows :

$$Fx(t) \;=\; \left\{ \begin{array}{ll} F_{x1} & 0 < t < t_1 \\ F_{x2} & t_1 > t > t_2 \\ F_{x3} & t > t_2 \end{array} \right\} \qquad (10)$$

Taking Laplace integral and Laplace Transform of the driving force using t-shifting theorem

$$F_x(s) = \frac{F_{x1}}{s} - \frac{(F_{x1} - F_{x2})}{s} e^{-t1s} + \frac{(F_{x3} - F_{x2})}{s} e^{-t2s}$$

The solution for equation of motion for LDM in triple stage approach is given by

$$x(t) = L^{-1} G(s) F_x(s)$$

$$x(t) = \frac{F_{x1}}{k}\left[1 - e^{-at}\cos bt - \frac{a}{b} e^{-at}\sin bt\right]$$

$$-\frac{(F_{x1} - F_{x2})}{k}\left[1 - e^{-a(t-t_1)}\cos b(t - t_1) - \frac{a}{b} e^{-a(t-t_1)}\sin b(t - t_1)\right]$$

$$+\frac{(F_{x3} - F_{x2})}{k}\left[1 - e^{-a(t-t_2)}\cos b(t - t_2) - \frac{a}{b} e^{-a(t-t_2)}\sin b(t - t_2)\right] \quad (11)$$

Quadruple Stage Force Approach

In triple stage force approach, the reversed signal help to eliminate overshoot. However, the motor moves slightly reverse before it maintains at the desired position. In order to eliminate the reverse movement, quadruple stage force approach was introduced. Quadruple stage force approach employs four different values of duty cycle in a single PWM signal. The third duty cycle is added to remove the reverse movement by sending forward signal with same magnitude as reverse signal (Norhisam *et al,* 2006). Quadruple stage PWM driving signal is shown in Figure 6.

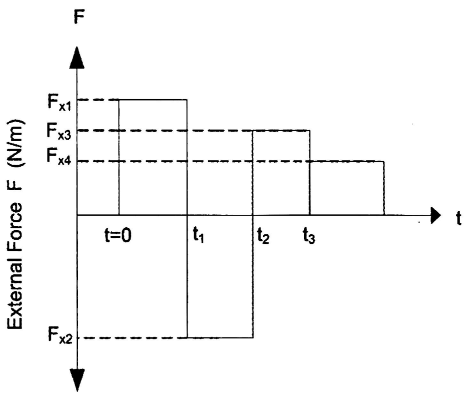


***Figure 6.** Quadruple stage PWM driving signal*

The non periodic function for external forces can be written as follows :

$$F_x(t) = \begin{Bmatrix} F_{x1} & 0 < t < t_1 \\ F_{x2} & t_1 > t > t_2 \\ F_{x3} & t_2 < t < t_3 \\ F_{x4} & t > t_3 \end{Bmatrix} \quad (12)$$

Taking Laplace Integral and Laplace Transform of the driving force using t-shifting theorem

$$F_x(s) = \frac{F_{x1}}{s} - \frac{(F_{x1} - F_{x2})}{s} e^{-t1s} + \frac{(F_{x3} - F_{x2})}{s} e^{-t2s} - \frac{F_{x3}}{s} e^{-t3s}$$

Finally, the solution for equation of motion for LDM in quadruple stage approach is given by :

$$x(t) = L^{-1} G(s)\, F_x(s)$$

$$\begin{aligned} x(t) = {} & \frac{F_{x1}}{k}\left[1 - e^{-at}\cos bt - \frac{a}{b} e^{-at}\sin bt\right] - \frac{(F_{x1} - F_{x2})}{k}\left[1 - e^{-a(t-t_1)}\cos b(t - t_1) - \frac{a}{b} e^{-a(t-t_1)}\sin b(t - t_1)\right] \\ & + \frac{(F_{x3} - F_{x2})}{k}\left[1 - e^{-a(t-t_2)}\cos b(t - t_2) - \frac{a}{b} e^{-a(t-t_2)}\sin b(t - t_2)\right] \\ & - \frac{(F_{x3} - F_{x4})}{k}\left[1 - e^{-a(t-t_3)}\cos b(t - t_3) - \frac{a}{b} e^{-a(t-t_3)}\sin b(t - t_3)\right] \end{aligned} \quad (13)$$

PERFORMANCE OF SENSOR LESS LINEAR DC MOTOR

Characteristics of PWM's Duty Cycle

All approaches for controlling the LDM position were designed by manipulating PWM signal. Manipulation of PWM signal was made by varying the value of duty cycle which varies the current supplied to the motor. Each value of duty cycle give certain value of LDM's displacement. Figure 7 shows relationship of LDM displacement (x) at various values of duty cycle (%D). For example, to obtain displacement of 10mm, the duty cycle of PWM is 15% and the current flowing in the coil is about 0.5A.

Single Stage Force Approach

In this research, the equation of motion for LDM has been simulated using Matlab software. The result from Matlab simulation will be used to study the behaviour of the system and proper adjustment will be made to the control parameter to obtain optimal performance of the system. By using single stage force approach, various values of duty cycle was selected to find relationship between PWM duty cycle (D) and LDM displacement (x). Figure 7 shows that

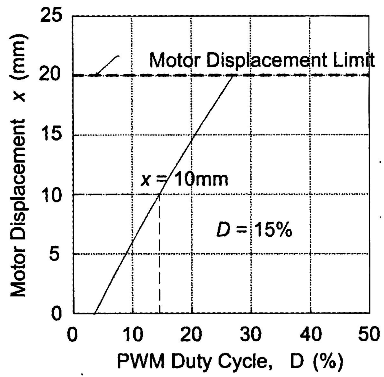


Figure 7. *PWM duty cycles motor displacement and current flowing*

to achieve displacement of 10mm, PWM's duty cycle of 15% need to be applied to LDM. From single stage force approach, value of rise time and settling time for the system are 50ms and 70ms respectively. Single stage force approach gives a slow transient response with overshoot about 2%.

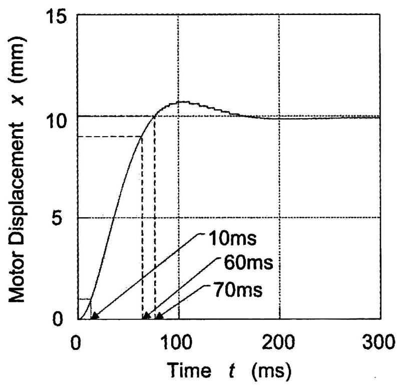


Figure 8. *System response in single stage force approach*

Dual Stage Force Approach

Dual stage approach employs two different values of duty cycle in a single PWM signal. The intention of first duty cycle is to reduce the rise time of the transient response while the second duty cycle is used to maintain the position of the motor at desired position (Norhisam *et al*, 2006). In order to reduce the rise time of the response, the first duty cycle should have the highest possible value in time duration of t_1. The time duration for the first duty cycle t_1 will determine the transient response of the system. Figure 9 shows the time response of the system using dual stage approach for different periods of the first duty cycle t_1 measured from Matlab simulation. By decreasing the period of the first duty cycle t_1, the overshoot also decreased. Unfortunately, by decreasing the period of the first duty cycle, the rise time of the response became higher.

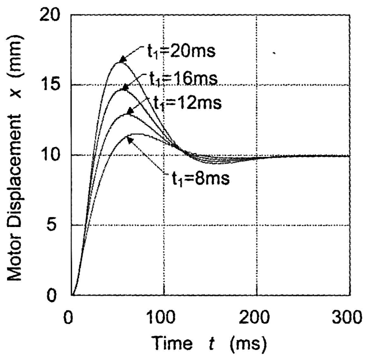


Figure 9. *System response in dual stage force approach at various values of* t_1

Triple Stage Force Approach

Triple stage approach was designed with intention to eliminate the overshoot produced by dual stage approach while maintaining fast rise time (Norhisam *et al,* 2006). In triple stage approach, three different values of duty cycle were used in a single PWM signal. The first duty cycle is used to reduce the rise time of the response while the second duty cycle is to reduce the inertia effect of the moving coil. The third duty cycle is used to maintain the motor at desired position.

In dual stage approach, the fastest response was obtained when t_1 = 20ms. The same value and time period also apply for the first duty cycle in triple stage approach. The second duty cycle has the same magnitude as the first duty cycle but in reverse direction. The value for the third duty cycle was set at 15% to maintain the position of the motor at 10 mm. The time period for the second duty cycle t_2 has been choosen randomly and the response of the motor was observed. Based on Figure 10, the best response for triple stage approach was achieved when t_1 = 20ms and t_2 = 8ms. The rise time t_r is about 18ms and settling time t_s approximately 75ms. However, there is some reverse movement about 8% before the motor reach and maintain at final desired position.

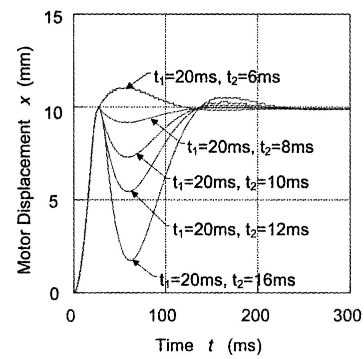


Figure 10. *Time response performance of triple stage approach for different values of* t_2

Quadruple Stage Force Approach

Quadruple stage driving signal consists of four different values of duty cycle in a single PWM signal. The first and second duty cycles follow as triple stage approach. The third duty cycle is added to remove the reverse motion by sending forward signal with the same magnitude as the first and second duty cycles. The fourth duty cycle is set at 15% to maintain the motor at desired position.

Figure 11 shows the time response for quadruple stage approach for different values of t_3 measured from Matlab simulation. The best response for quadruple stage approach was achieved when using t_1 = 20ms, t_2 = 8ms and t_3 = 2ms as shown in Figure 10. The rise time t_r is about 18ms and settling time t_s approximately 32ms with no overshoot and no steady state error.

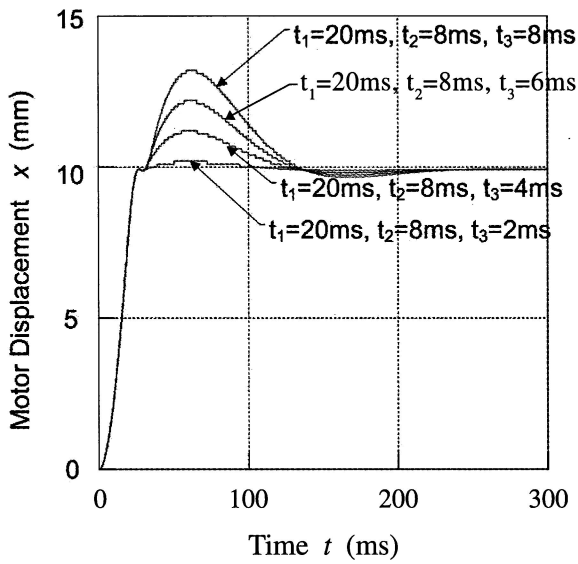
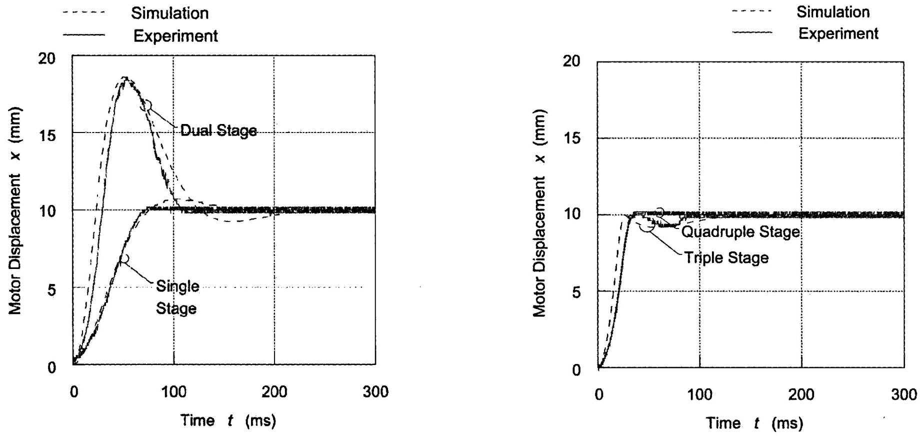


Figure 11. *System response based on various values of* t_1, t_2 *and* t_3

Effect of Force Stages Approach to the System Performance

The positioning expression for sensor less LDM had been simulated by using Matlab software and the experimental procedure done by Norhisam *et al*(2006). Comparison between simulation and experimental result had been made. It was shown that the simulation and experimental result gave the same pattern for all force stages.



(a) Single and dual stage performance *(b) Triple and quadruple stage performance*

Figure 12. *Comparison between simulation and experiment result*

Table 1. Performance comparison of four approaches

Force Approach	**Rise time,** t_r (ms)	**Settling time,** t_s (ms)	**Overshoot,** OS(%)
Single stage	50	70	0
Dual stage	20	100	80
Triple Stage	18	75	0
Quadruple stage	18	32	0

CONCLUSION

Summary of the performance for each stage force approach used is shown in Table 1. It shows that every higher force stage had improved the transient response of the system compared to the previous force stage. In dual stage force approach, the rise time of the system had improved 60% compared to single stage force approach. But an overshoot occurred in this force stage which is about 80%. The overshoot problem was solved using triple stage force approach. But in this force approach, there is reverse movement before the motor reached its final displacement. By using quadruple stage force approach, besides eliminating the reverse movement, it improved about 50% of the settling time compared to the triple stage force approach.

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Abstract. The abstract should precede the article and, in approximately 150 words, outline briefly the objectives and main conclusions of the paper. It should be followed by no more than 10 keywords (separated by commas) identifying the matter for retrieval systems.

General Form. Papers reporting original research should be cast in the form: Introduction - Materials and Methods - Results and Discussion - Conclusion - Acknowledgements - References. Reviews and short communications need not follow this arrangement.

References. References in the text should be denoted by giving the name(s) of the author(s) with year of publication in parentheses. If there are more than two authors, it is in order to put "*et al*" after the first name.

Bibliographical references should be listed in alphabetical order of author at the end of the paper. The following style should be adopted:

Journal citation: Chan, T.K., Herlina, S. and Ruangsap, B. (1993). Cloning of promoter sequences from *Escherichia coli*. *J. Mol. Biol.* **45**: pp 567-575.

Book: Chan, T.K. (1992). Plasmids of enterobacteria. In: *Pathogenesis of bacterial infections*, ed. Ramirez, A. and Aquino, S., Protea Press, Kuala Lumpur, pp 235-245.

Report: Dubin, F.S., Mindell, H.L. and Bloome, S. (1976). *How to save energy and cut costs in existing industrial and commercial buildings.* An energy conservation report, May, Noyes Data Corporation, Park Ridge, USA.

Illustrations. All illustrations should be photographed in sharp black and white, high-contrast, glossy prints. Illustrations (including formulae) generated using computer programs should be saved in JPEG/TIFF format, they may also be scanned (300 dpi). Graphs and diagrams should be large enough to permit 50% reduction and be numbered consecutively in the same order as in the text, where they should be referred as "Figure" and not "Fig.". Legends for figures should be listed consecutively on separate sheet of paper.

Tables. These should have short descriptive titles, be self-explanatory and typed on separate sheets. They should be as concise as possible and not larger than a journal page.

Units, symbols, abbreviations and conventions. These must follow SI units.

The Editor reserves the right to make literary corrections and adjust style for uniformity.

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