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# Modified Loop Shaping Algorithm in Designing 2-DOF Controller of a Ladder-Secondary Double-Sided Linear Induction Motors

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**ABSTRACT**

This paper proposes an innovative algorithm for designing 2-DOF robust controllers which are supported by loop shaping concept. It plays an important role at current mechatronics from the requirement of the high productivities, the high qualities of products and the total cost reduction. For getting precision control, 2-DOF control structure should be suitable for achieving two goals of control aims; fast response and precision movement. The 2-DOF controllers provide better results for the controllers, especially for improvement of precision perspectives and smaller settling time.

**Key words:** Double-sided linear induction motor, 2-DOF controller, Loop shaping approximation

## 1. INTRODUCTION

Currently, mechanical linear motion systems, a device for processing of semiconductor component, mostly need high-speed or high-accuracy linear motions. Some linear motion systems employ rotary motors with mechanical transmission components, such as reduction gears and lead screw. Those mechanical transmissions are not only providing some ripples on linear motion velocity and dynamic response significantly, but also generate phenomena of backlash, large frictional and inertial loads, and structural flexibility. Therefore the use of direct drive linear motors, which exclude the use of mechanical transmissions, provide some advantages for widespread employ in high-speed or high-accuracy positioning control systems [1]–[3].

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Linear induction motors can be clasified as electrical machines that transfer electrical energy into the mechanical one of translatory moving. The one of type LIMs is a double-sided linear induction motor (DSLIM). These machines have special structure that consist of two primary parts and single stationary part. With short primary part, and ladder seconadry have been designed and manufactured for precision motion purposes [4,5]. Study of precision motion that caused by cogging forces in DSLIM have been conducted by authors [6,7].

Due to phenomena of longitudinal end effects in a linear motor, its motion is not smooth and generates ripples disturbances as it moves. Significant effort has been devoted to solving the difficulties in controlling linear motors [8] [9]. Early work includes the based linear robust control methods as proposed by Alter and Tsao in [1]-[2], the disturbance observer (DOB) [9] based disturbance compensation method in [8], and feed-forward nonlinear ripple force compensation in [3]. A precision motion control can also be improved by modifying the three-phase inverter equipment. By reducing the total harmonic distortion (THD), the precision of motion for AC motors can be increased. The Fuzzy logic controller can be employed for reducing THD and dc-link utilization is improved. The study also shows the comparison between the PI controller-algorithm and the fuzzy logic algorithm [10]. PID-Robust have also implemented for precision motion control of electrical motor. Controller parameters of PID have tuned by robust concept, so that the motion of position control cannot be influenced by load-variation [11].

For using a linear motor for linear motion control perspectives, fast response with high precision control motion performance is an unavoidable requirement [12]. The improvement of the precision motion control, for instance, is aimed for achieving of high-performance mechatronic systems including micro- and/or nano-scale motions. In addition, it is also aimed to manufacture some devices which it can have characteristics of high productivity, high quality of products, and total cost reduction. In related to the precision motion control, the required specifications in motion performance, e.g., response/settling time and trajectory/settling accuracy, should be sufficiently achieved [13].

The required characteristics in linear motion performance, e.g. settling time and set-point trajectories should be achieved as small as possible. The level of robust against disturbances and/or uncertainties should be the essential performances added for high performance. An essential approach for achieving fast and precision motion performance is to wide the control bandwidth of a feedback control systems. A higher bandwidth can make the system to be more robust against disturbances and/or uncertainty. However dead-time or delays components, and varieties of nonlinearities generally prevent the control bandwidth from being wider than the viewpoint of systems stability.

Two-DOF (Degree of Freedom) control framework with a combination of feedback and feed-forward compensators should be a practical technique for achieving desired high motion performance. The feedback controller design-algorithm is aimed for achieving a stability robust and based on an uncertainty model of controlled process. Separately, the feed-forward design refers to the loop shaping concept. So, combination of two design-algorithms, will result to precision and fast systems for a linear movement application [14].

Linear induction motors are implemented for widest applications for precision motion control purposes, especially for a double-sided linear induction motor. For instance, in the transportation systems, the double-sided linear induction motor with flat-secondary Industrial tests, like accelerating aircrafts and manufacturing processes. Some kind of machine tools are the other important utilizations of LIMs [15]. This widely applications has provided the idea for previous researcher to investigate more intensive on it for command shaping control, and produce some papers on DSLIM [16]. This paper develops the other shaping concept, loopshaping design algorithm of DSLIM using 2-DOF (Dimension of Freedom) control system structure .

## 2. PROPOSED 2 DOF STRUCTURE

Figure 1 shows a 2-DOF control system, in which one controller is placed in forward path that is directly connected to set-point variable. The other one is connected to error variable of control system

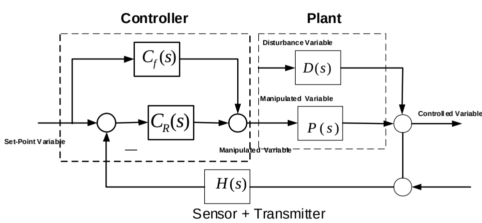



**Figure 1:** Standard 2-DOF Control Structure

Based on 2-DOF structure shown in Figure 1, the process design is divided into 2 objectives, such as tracking problem and disturbance rejection problem. Both problems commonly are solved separately. The tracking problem requires as large as possible of the system gain. A large gain system provides an improvement of stability level. However, noise signals in this case will flow in the inside of system which can generate internal disturbance of the systems.

For 2-DOF structure, a Closed loop control system consist of two kind of controllers. The first controller $C_1$ is to handle the velocity error so that response system is quicker to achieve steady condition. The second controller input $C_2$ is aimed to coverage the internal (disturbance robust uncertainty) robust of system.

The response performance can be described into sensitivity mathematical sensitivity (S) and overall transfer system (T). For this case sensitivity and system might be presented into two mathematical equations. It is shown by equation (1).

$$S = \frac{1}{1+G_1C_2}; T = 1 - S \tag{1}$$

The connectivity between output controlled system – variable of the linear velocity - and set-point input signals are represented by equation (2).

$$T_{VY} = G_v S C_1 \tag{2}$$

The other connectivity between error variable and desired input can be presented in (3).

$$T_{er} = T_{VY} - M = G_v S C_1 - M \tag{3}$$

Based on the mathematical in (3), controller $C_1$ can be calculated. If the components of system $G_v$ and $M$ are known, and mathematical sensitivity of system as performace are given, so that the controller $C_1$ can be determined using equation (4).

$$C_1 = G_v \frac{M}{G_v S} \tag{4}$$

If M is an expected mathematical model, in related with the equation (3), connectivity between model-error and both controllers can be formulated in equation (5).

$$\bar{T}_{er} = \frac{G_v C_1}{1+\tilde{G}_v C_2} - M \tag{5}$$

Based on equation (5), the mathematical controller $C_2$ therefore can be obtained easily.

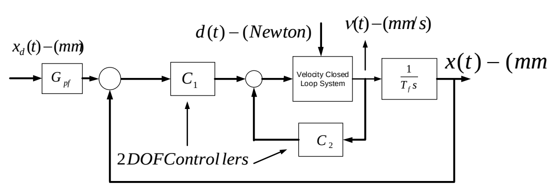



**Figure 2:** Proposed 2-DOF Control Structure

Figure 2 illustrates the proposed DSLIM which is employed as the test-bed for the experiments. It has 9 ladder-bars and 10 winding slots of primary parts (double-sides). The physical primary parts are shown in Figure 3. The physical design of this motor has been conducted in [15-16]. Controller of this system is placed in the feedback path and in the loop path of the system. Figure 2 shows the closed loop feedback system with 2 controllers; one of them is connected to the output system linear with a velocity of the motor, x(t). The second controller is placed in the output of the summing point.

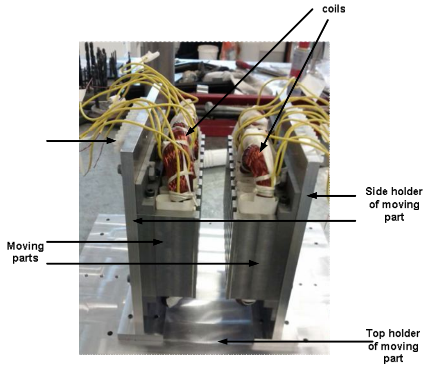



**Figure 3 :**Manufactured Moving Part of DSLIM

## 3. MATHEMATICAL MODEL OF DSLIM

The principal of mathematical model of DSLIM is represented by the relationship between Q-axis voltage to linear speed of the moving part. The relationship between q-current ( $i_q$ ) with the q-voltage can described by a second order differential as shown in equation (6).

$$T_q \frac{di_q}{dt} + i_q = v_q - K_x v_x \qquad (6)$$

where $T_q$ is the time constant of q-axis circuit, $i_q$ is the Q-axis current variation and $v_q$ is the input voltage of Q-axis circuit and $K_x$ is the factor of EMF induced voltage If it is assumed that all variables in equation (6) are initially set to zero values, the relationship between the voltage input and current can be transformed into a Laplace equation.

The mathematical model which illustrates these relationships is described by equation (7).

$$I_q(s) = \frac{V_q(s)}{T_q s + 1} \qquad (7)$$

The relationship between the thrust force and q-current can be done by measure both variables directly on the test-bed experiment. Based on the measurement data on testbed, connectivity between thrust force and q-current is shown by equation (8).

$$F_x = 24.50 I_q \qquad (8)$$

Based on Newton Rule number 2, that the linear speed can be represented as an integral of thrust force. The proportional factor of this relationship is opposite by the mass of the moving part of DSLIM. The mathematical equation of them is presented by equation (9):

$$v_x = \frac{1}{m} \int F_x dt \qquad (9)$$

Based on equations (7), (8) and (9), the block diagram of the relationship between Q-axis voltage to linear speed is described into Figure 4.

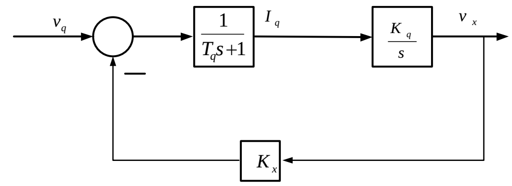



**Figure 4:** Structure of Current Loop

The moving part time constant $T_q$ can directly be obtained from the Baldor controller. The parameter of $K_q$ is a mass of moving part of motor. The value of parameters $T_g$ is 0.002312 sec. and $K_q$ is 0.036364. The parameter of $K_x$ is estimated by investigation the relationship between linear speed and the Q-axis voltage (Vq- Command signals) of Baldor Controller.

The validation of the mathematical model of DSLIM can be conducted by comparing the linear speed of motor with the output of model motor with similar input signals. Figure 5 shows the Vq-command signals of motor (it is taken from memory of Baldor Controller).

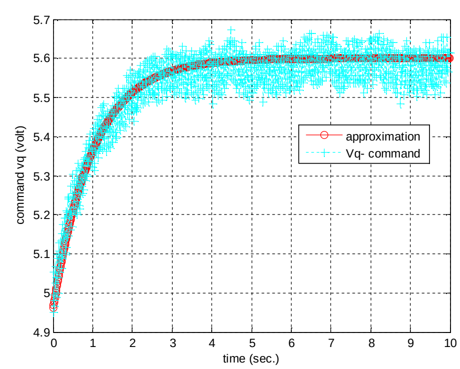



**Figure 5 :The Current Controller Output**

The signals shown in Figure 5 illustrates the current controllers. The red curve represents the curve of the Vq-Command. For estimation of the mathematical model of motor, the input of model is provided by the approximation of Vq command signals (red curve).

The output of the model should agree with the linear speed of motor. Since the moving time constant is very small, the electrical circuit transfer function can be neglected for simplifying the analysis. Therefore, the model shown in Figures 6 and 8 can be simplified into the second order of transfer function. The simplified transfer function is shown in equation (10).

$$\frac{V_x}{V_q} = \left(\frac{1}{K_x}\right) \frac{1}{\frac{1}{K_q K_x} s + 1} \qquad (10)$$

Equation (10) shows that transfer function of motor which can be approximated into a first order equation. The parameters of the first transfer function are a Gain steady state $G_{mst}$ and a time constant. $T_{mst}$ An unknown parameter in the equation is feedback gain $K_x$. The parameter $K_x$ can be estimated, if the signal output of real motor (speed) is measured.

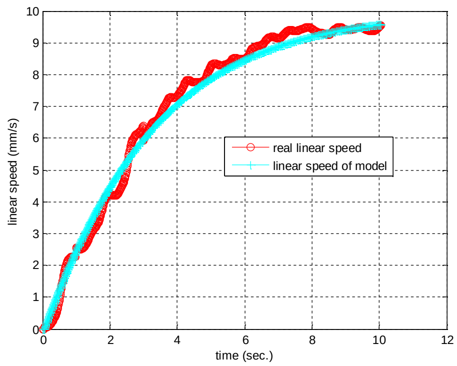
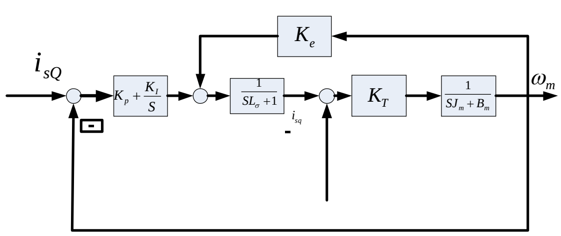



**Figure 6 :**Current dynamic of DSLIM

The real linear speed of the motor is already measured and recorded. Figure 6 shows the measured linear speed. In order for the output of the model to have a exact similar shape as the real linear speed curve shape, the real curve has to be approximated as a first order mathematical differential equation. Based on the experiment-data, the DC-Gain and time constant are $10/5.6 = 1.786$ and 4.9 sec respectively.

Based on the both parameters, the parameter $K_x$ is 0.56. For mathematical model validation, the comparison between real linear speed of DSLIM with the output of mathematical model are compared. The comparison results show that the average error between real linear speed and mathematical model is 3.9%.

Figure 7 describes the decoupling process. In the right site, the real diagram block, and in the left site consist of the controller-decoupling. Using the combination transfer function R, the complicated model can be changed into the sinple one. Figure 7 shows the modified diagram block of DSLIM.




$$P_{nom} = \frac{K_T / B_m}{(ST_e + 1)(ST_m + 1)}$$

**Figure 7 :Modified Plant Process**

The nominal plant is:

$$\tilde{P} = \frac{0.43/(0.53*1.3*0.19)}{s^2 + (2*1.499*2.02)s + 2.02^2} \quad (11a)$$

And real plant is:

$$P = \frac{0.43/(0.53*1.3*0.19)}{s^2 + (2*0.9*2.02)s + 2.02^2} \quad (11b)$$

## 4. FORMULATION OF L – LOOP TRANSFER

Commonly, the objective of the robust-controller design is to obtain the controller transfer function $C(s)$ so that a system closed loop has internally stabil and achieve the robust performance. In the loop shaping method, The idea is to construct the loop transfer L to achieve the approximated condition of the inequality equation

$$\left\| |W_1 S| + |W_2 T| \right\|_\infty < 1 \quad (12)$$

The calculation of controller $C(s)$ can be found by the use of a relationship $C = L/P$. The underlying constraint are internally stabilized of the nominal feedback system and properness of $C(s)$, therefore L is not freely assignable. In terms of Loop transfer (L) and both weighting function, robust performance can be written into:

$$\Gamma(j\omega) = \left| \frac{W_1(j\omega)}{1 + L(j\omega)} \right| + \left| \frac{W_2(j\omega)L(j\omega)}{1 + L(j\omega)} \right| < 1 \quad (13)$$

wiith:

$$\min\{|W_1|, |W_2|\} < 1 \quad (14)$$

In order to equation (13) and (14) are divided by term $1 + |L|$ and $|1 - |L||$, both equation can be written into one equation:

$$\frac{|W_1| + |W_2 L|}{1 + |L|} \le \Gamma \le \frac{|W_1| + |W_2 L|}{|1 - |L||} \quad (15)$$

Suppose that $|W_2| < 1$, so from equation 16 in term of L become**:**

$$\Gamma < 1 \Leftarrow |L| > \frac{|W_1| + 1}{1 - |W_2|} \quad (16)$$

## 5. WEIGHTING FUNCTIONS

In this case, the weighting function can be defined as band pass filter. That is due to the specification performance is expected in the range frequency 0,1 rad/s. The specifical plant for DSLIM (double-sided linear induction motor) will be subtituted in the end of calculation process, which is done using C=L/P (L= loopshape and P is transfer function of controlled system – plant). For simplicity of calcultaion, the weighting function $|W_2(s)|$ is defined as equation (17).

$$W_2(s) = \frac{s+1}{20(0.01s+1)} \quad (17)$$

This weighting function shown in equation (17) is upper bound on the magnitude of the relative plant pertubation at frequency $\omega$. For this function, it is defined that the magnitude of pertubation starts at 0.05 and increases monotically up to 5 crossing 1 at 20 rad/s. In order for obtaining the transient performance good tracking, the reference in this simulation will be defined as the sinusoidal function for range frequency 0 to 1 rad/s. For getting the good tracking problem for the sinusoidal refernce, the weighting function $W_1(s)$ should have constant magnitude at frequency between 0-1 rad/s. If the normal feedback system is internally stabil, then inequality equation 18 will be hold,

$$\|W_2T\|_\infty < 1 \text{ and } \left\|\frac{W_1S}{1+\Delta W_2T}\right\|_\infty < 1 \qquad \forall\Delta \quad (18)$$

If and only if the equation (19) is hold.

$$\left\||W_1S| + |W_2T|\right\|_\infty < 1 \quad (19)$$

Using above justiification, the weighting function $W_1(s)$ can be determined as first orde function with its characterstics is shown equation (20).

$$|W_1(j\omega)| = \begin{cases} a, & if \quad 0 \le \omega \le 1 \\ 0, & else \end{cases} \quad (20)$$

This design of feedback control is aimed to have system response so quick as possible, so the open loop transfer function should be defined in a first order function, that is shown in equation (21).

$$L(s) = \frac{b}{cs+1} \quad (21)$$

It is reasonable to take c=1 so that $|L|$ starts rolling off near the upper end of the operating band taht is frequency between 0 – 1 rad/s. The b parameter is defined as the constrain for the magnitude of tracking problem. This parameter should be as larger as possible for good tracking. The largest value of b is based on: -

$$|L| \le \frac{1-|W_1|}{|W_2|} = \frac{1}{|W_2|}, \qquad \omega \ge 20(rad/s) \quad (22)$$

provides value of 20, so the open loop transfer function is

$$L(s) = \frac{20}{s+1} \quad (23)$$

For verification of robust performance level, the a parameter should be choosen at as large as possible, so that value of:

$$|L| \ge \frac{a}{1-|W_2|}, \qquad \omega \le 1 \quad (24)$$

And the function of

$$\frac{a}{1-|W_2(j\omega)|} \quad (25)$$

Is increasing over the range [0,1], while $|L(j\omega)|$ is decreasing. Therefore a-value might be found by solve the equation:

$$|L(j1)| = \frac{a}{1-[W_2(j1)]} \quad (26)$$

Based on the bode diagram of the weighting function and the open loop transfer function, the a-value can be defined as a=15.5.

## 6. ROBUST PERFORMANCE VERIFICATION

The loop transfer $|L(j\omega)|$ that have been calculated on above section, should be verificated of its robust performance. At first step, equation (18) has to be made in Bode Dagram form.

$$|W_1(j\omega)S(j\omega)| + |W_2(j\omega)T(j\omega)| \quad (27)$$

Its maximum value is 0.92. Since this value is under 1-value. So the robust performance is verified. Based on the previous calculation, the weighting function $W_1(s)$ can be formulated as equation (25).

$$|W_1(j\omega)| = \begin{cases} 13.35 & if \quad 0 \le \omega \le 1 \\ 0, & else \end{cases} \quad (28)$$

With the open loop transfer function shown equation (7), the tracking error is then 7.3%. For the presicion purposes, the tracking error of 7.3% is still too large. To improve the precision, make $|L|$ larger over the frequency range between 0-1 rad/s. the the the robust performnace is achieved. Therefore, $|L|$ could be changed into equation 26.

$$L(s) = \frac{s+10}{s+1}\frac{20}{s+1} \quad (29)$$

The factor $(s+10)/(s+1)$ in equation (29) has magntidue nearly 10 in the frequency range 0-1 rad/s, and will be rolled of above 10 rad/s. If the weighting function function $W_1(s)$ use equation (28), and a-parameter is calculated which gives a=94.36 so tracking error is reduced to 1.07%.

## 7. RESULTS AND DISCUSSION

Simulation verification of 2-DOF controllers design have been conducted using MATLAB. Verification was done and shows that the responses of system are exact similar with the expected specification design. The input test signals are step function, sinusoidal and ramp signals. Figure 5 illustrates the plant outputs for various damping ratios. It also describes the characteristic of plant if input signals are given in various magnitude for sinusoidal and exponential signals. The verification results show that the performance of the closed loop system with 2-DOF controllers can be implemented into linear speed motion control system by loop-shaping method.

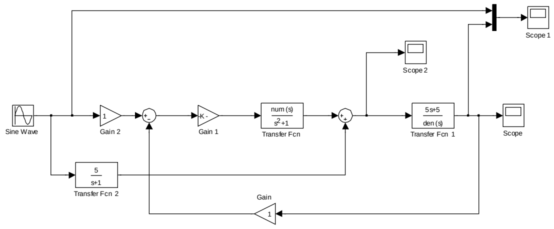



**Figure 8:**Simulation Verification of 2-DOF Structures

Figure 8 shows a simulation of closed loop control system with two controllers (2-DOF). The controlled system part (plant component) is simulated by varying the damping ratio of plant. The measurement of the controlled system output are aimed to observe the overshoot maximum of linear speed variable if motor currents is changed. Fig. 6 presents the controlled system output if damping ratio plant are varied.

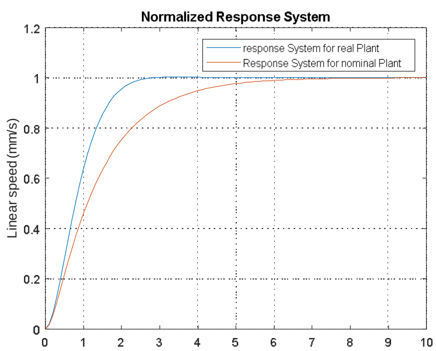



**Figure 9:** Simulation Results

Figures 8 and 9 show that the actual linear speed of motor can follow the set-point of some trajectories accurately. It illlustrates also that the results of 2-DOF controllers has been compared to the response with control system which has only one DOF controller. It reaches the desired final linear speeed at the specified settling time. On the tracking problem of the figure, it shows a close-up view of the tracking with a linear speed resolution of 2 mm/s per division. The speed curve in Fig. 7 shows that the actual motion trajectory follows very well with the desired motion profile. From both Figs. 7 and 8, we observe that the achievable error speed reaches 0.01% for 2-DOF structure and 2.2% for 1-DOF structure.

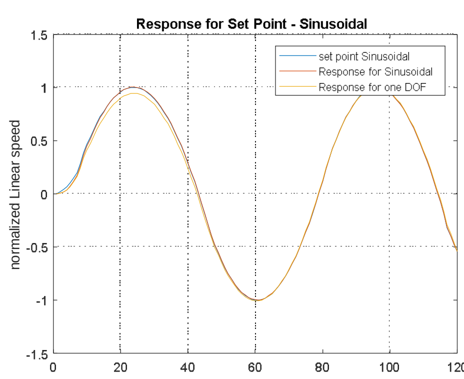



**Figure 10 :**Responses for set-point of Sinusoidal Signals

Figure 10 shows that the system can follow the trajectory of sinusoidal signals as the set-point. The maximum error between the set-point signals and system outputs are located in the maximum magnitude of sinusoidal signals. The damping ratio for this simulation have been varied. Fig 11 shows the comparison of response for 2-DOF and 1-DOF structure with exponential signals as set-point. It illustrates that the 1-DOF structure generates more error linear than using the 2-DOF structure by loop-shaping method. The 2-DOF precision linear speed for setpoint exponential is less than 1-DOF structure. The erroe-transient of trayectory for 2-DOF is 0.002%, for 2-Dof 2.12%.

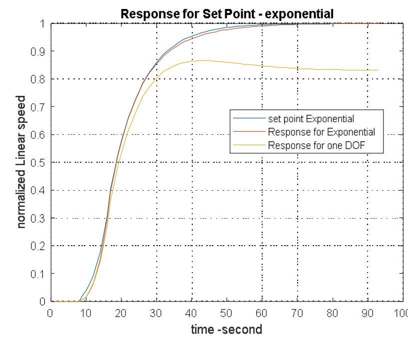



**Figure 11 Responses for set-point Exponential Signals**

## 8. CONCLUSION

In this paper, an innovative loop shaping algorithm has been implemented in motion control linear speed control using 2-DOF. Both design controllers have been calculated based on loop shaping concept. The calculation of 2-DOF controllers are done by the consideration of the variation of internal plant-parameters (robust controllers). The drive of system employs a ladder-secondary double-sided linear induction motor. The results have been realized in MATLAB-simulation and shows that the system always stabile, even though plant-parameters are varied. Design-algorithm results have also been verified with consideration of parameter model variations (Robustness performance). The 2-DOF control system shows that the tracking problem can be solved and the steady state performance can be achieved for sinusoidal signals as set point and also for exponential signals. The damping ratio parameter of model have been changed from 0.9 to 1.5, and closed loop system provided stabile good and precision performance.

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