A Theoretical Study of the Self Reinforcement Brake System

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Abstract: The main aim of this paper is to study the performance of the self-reinforcement Electronic Wedge Brake system (EWB) which is one of the Brake-By-Wire applications. A mathematical model was created to simulate the full electronic wedge brake system containing its common components (the DC motor, the roller screw and the wedge brake construction). The mathematical model was applied on MATLAB program SIMULINK file to consider the inputs and outputs of the system for studying the wedge brake system performance. According to the state space equation, the inputs vary according to the simulated operating conditions. These variables mainly are; the input voltage, the wedge angle, and the coefficient of friction. All results of theoretical study are presented and discussed and the appropriate operating conditions of the system are concluded.

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Key words: Electronic Wedge Brake, Brake-By-Wire, Braking performance, SIMULINK**.**

1. Introduction

The principle of braking by wire is based on separating the hydraulic connections between the brake pedal and the wheel brake and replacing it with electrical signals. The function of the brake by wire is compatible with other electronic systems such as Anti-lock Braking System (ABS). The driver desire to brake the vehicle is recognized by a sensor that delivers a signal according to the pedal stroke which is transmitted to the brake controller. The brake controller then generates signal to the wheel actuator.

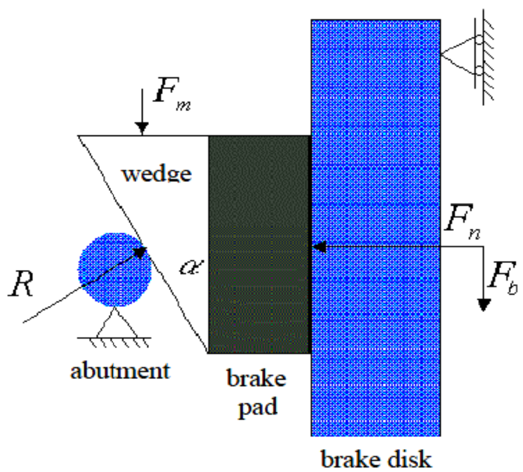

Figure (1): Simple model for the wedge brake concept [1]

Figure (1) illustrates a simple model of wedge brake concept. The brake lining is equipped with a wedge on its backside which rests on an abutment. The actuator presses the brake lining in between the abutment and the brake disc with the motor force (F_M). The braking force (F_B) resulting from the contact between the brake disc and the brake lining acts in the same direction as the motor force which results in the anticipated self-reinforcement.

By comparing the Electronic Wedge Brake with the conventional brake, the braking force generated by the wedge will be much higher than the conventional one; this lets the stopping distance to be shorter in wedge system than the conventional system.

The wedge brake philosophy, an auxiliary force derived from the self-reinforcement effect is used to build up the normal force. Therefore the braking actuator only has to supply a small portion of the required normal force. Furthermore the energy needed to widen the caliper is also taken from the vehicle's kinetic energy.

Figure (2) shows a comparison of the car stopping by these two types of brakes; brake distance from a speed of 80 km/hr decreases by 10 meters on an ice road with low coefficient of adhesion μ and low ambient temperature (0º).

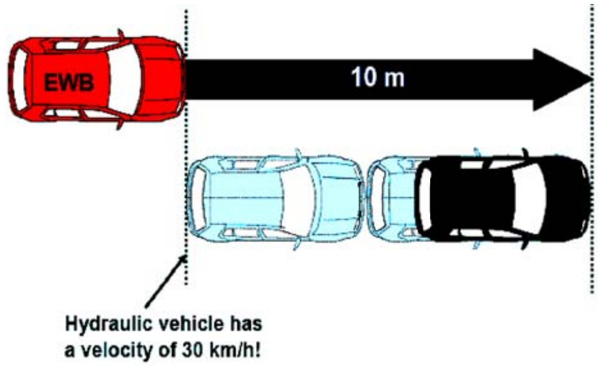

Figure (2): Difference in stopping distance by using the EWB [2]

Back ground

Force Analysis for a Simple Wedge Construction

Where:
F_A = Reaction Force,
F_B = Braking Force
F_N = Normal Force,
F_M = Motor Force.
F_W = Total Force on wedge.

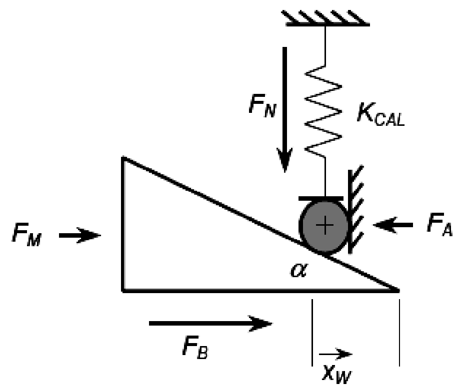

Figure (3): Force analysis on a simple wedge model [3]

The normal force to the brake disc:

$F_N = K_{CALLIPER} . X_W . \tan\alpha$

Assuming that the disc is rotating

$F_B = \mu . F_N = \mu . K_{CALLIPER} . X_W . \tan\alpha$

Due to the wedge angle there is reaction force in the axial direction F_A

$F_A = - F_N . \tan\alpha$

The total axial force acting on the wedge:

$F_W = (\mu - \tan\alpha) . F_N + F_M$

$= (\mu - \tan\alpha) . K_{CALLIPER} . X_W . \tan\alpha + F_M$

The equation of motion of the wedge brake model

A wedge brake model has been constructed for test purposes in laboratory; the model construction is a little different from the original design, this is shown by Fig. (4).

Force analysis

In X-Direction

$F_M + \mu . F_N - F_A . \sin\alpha = M_W . \dot{V}$

In Y-Direction

$F_A . \cos\alpha - F_N = M_W . \tan\alpha . \dot{V}_W$

By adding both equations

$F_M + \mu . F_N - F_A . \sin\alpha + F_A . \cos\alpha$

$- F_N = M_W . \dot{V}_W + M_W . \tan\alpha . \dot{V}_W$

$F_A = \frac{FN}{\cos\alpha} + M_W \frac{\tan\alpha}{\cos\alpha} \dot{V}_W$

$F_A . \cos\alpha = F_N + M_W . \tan\alpha . \dot{V}_W$

$F_A . \sin\alpha = \tan\alpha . F_N + M_W . \tan^2\alpha . \dot{V}_W$

By substituting in equation

$F_M + \mu . F_N - (F_N . \tan\alpha + M_W . \tan^2\alpha . \dot{V}_W) = M_W . \dot{V}_W$

$F_M + \mu . F_N - F_N . \tan\alpha - M_W . \tan^2\alpha \dot{V}_W = M_W . \dot{V}_W$

$M_W . \dot{V}_W + M_W . \tan^2\alpha \dot{V}_W = F_M + \mu . F_N - \tan\alpha F_N$

$M_W \dot{V}_W (1 + \tan^2\alpha) = F_M + (\mu - \tan\alpha) F_N$

as $F_N = K_{CALLIPER} . X . \tan\alpha$

$M_W \dot{V}_W (1+ \tan^2\alpha) = F_M + (\mu - \tan\alpha) . K_{CALLIPER} . \tan\alpha . X$

$\dot{V}_W = \frac{1}{M_W (1+\tan^2\alpha)} (F_M + (\mu - \tan\alpha) . K_{CALLIPER} . \tan\alpha . X)$

$\dot{V}_W = F_M \frac{1}{M_W (1+\tan^2\alpha)}$

$$+\frac{(\mu - \tan\alpha) . K_{CAL} . \tan\alpha}{Mw\,(1+\tan^2\alpha)} . X_W$$

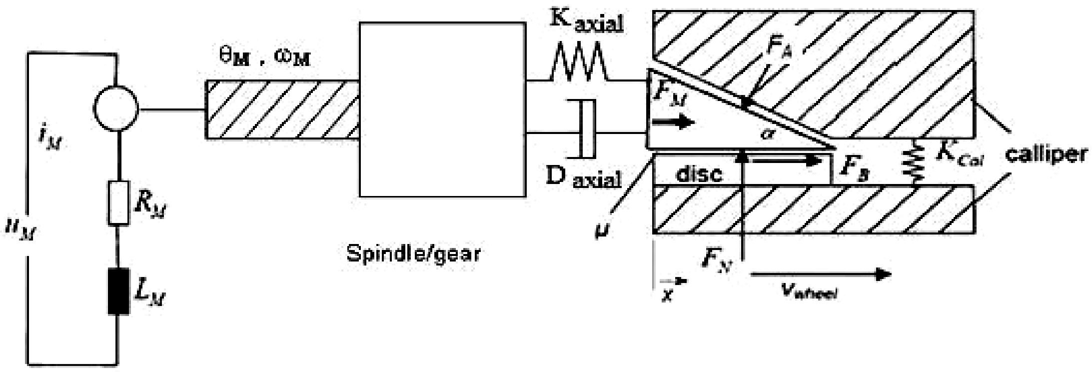

Figure (4): Electronic wedge brake model

$F_B = \mu . F_N$

$F_B = \mu . K_{CAl} . X_W . tan\alpha$

Output equation,

$Y = C X$

$C = \mu. K_{CALLIPER} . X_W . tan\alpha$

$$Y = [\mu\ K_{CALLIPER} . X_W . tan\alpha \quad 0] \begin{bmatrix} X_1 \\ X_2 \end{bmatrix}$$

Modeling by using MATLAB Program

The DC motor output force is the force that will excite the wedge brake system.

For the wedge brake system, the input force (F_M) will affect the system and the outputs will be wedge displacement (X_W) and force on wedge due to braking (F_B).

The influence of different input variable parameters for the wedge brake system will be studied and presented.

The wedge brake system consists of:

i. DC motor,

ii. A roller screw and

iii. Wedge construction.

iv. The wedge brake system construction

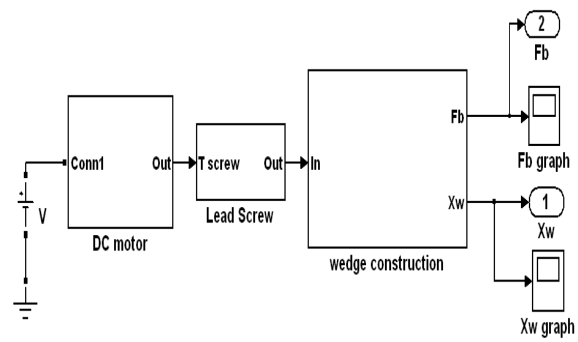

Figure (5): Wedge brake system outputs; braking Force (F_B) and wedge displacement (X_W).

The DC motor characteristics data are:

- *Rotor moment of inertia (J) = 0.01 kg.m²/s²*
- *Mechanical system damping ratio (b) = 0.1 N.*m.s
- *Electromotive force constant (K=Ke =Kt) = 0.01 Nm/Amp*
- *Electric resistance (R) = 1 ohm*
- *Electric inductance (L) = 0.5 H*
- *Input (V): Source Voltage*
- *Output (Te): DC motor Torque = T_{Screw}*

The Roller-Screw characteristics data are:

$$T_{SCREW} = \frac{L}{2\pi} . F_{SCREW} F_{SCREW}$$

Taking into consideration that

$F_{SCREW} = F_M$ and

Motor efficiency (η = 71 to 90 %).

- *Lead screw = 6*
- *Input source = T_{Screw} = DC motor Torque*

- $Output = F_{Screw} = F_{Motor}$

Table (1): The Roller Screw technical data sheet [4]

					NUT							SCREW		
Model	Lead	Pitch	Dynamic Co (kN)	Static Co (kN)	A⌀	B	C⌀ H6	D	E PCD	F Dia x No	G	H⌀	J⌀ min	Max Speed (rpm)
15	6	1	45	68	92	90	34	4	55	M8X6	12	17	15.3	5500
	12	2	35	52	92	90	34	4	55	M8X6	12	17	15.3	5500
20	6	1	58	87	103	110	45	4	58	M8X8	12	21	18.4	4900
	12	2	58	87	103	110	45	4	58	M8X8	12	21	18.4	4900
	18	3	50	74	103	110	45	4	58	M8X8	12	21	18.4	4900

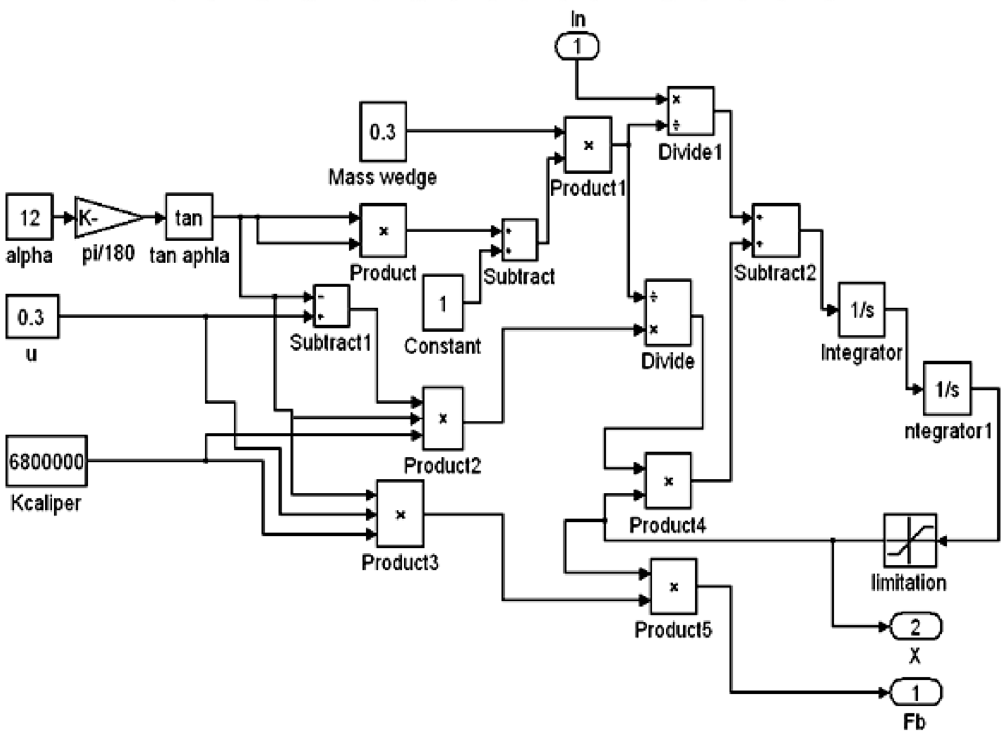

Figure (6): Wedge model construction with its variables parameters

Test Modeling Results

The input parameters will be varied one by one to study its influence of each parameter on wedge brake performance while the other parameters are fixed constant.

The input parameters are:

i. *The input voltage(V_{IN})*
ii. *The wedge angle (α)*
iii. *The coefficient of friction (μ)*

i. The Input Voltage (V_{IN})

It will vary according to the change of the electric resistance value of the potentiometer attached to the e-pedal and influenced by pedal travel. Variation of the input voltage (V_{IN}) to the DC motor will vary the Braking Force (F_B) and the Wedge Displacement (X_W).

Table (2) Values of input voltage affected by variation of e-pedal stroke

e-pedal stroke	input voltage (V_{IN})
¼ stroke	18 V
½ stroke	20 V
¾ stroke	22 V
Full stroke	24 V

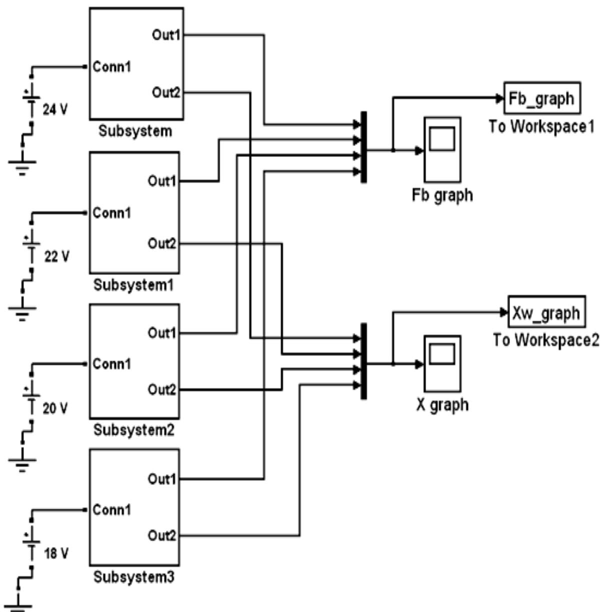

Figure (7): SIMULINK model of the system with Voltage (V_{IN}) as system input and will be the Braking Force (F_B) and Wedge Displacement (X_W) as outputs

Other parameters will be considered as constant inputs to the model (the wedge angle α = 12º, the coefficient of friction μ = 0.3, the wedge mass M_W = 0.3 Kg, and the caliper stiffness $K_{CALLIPER}$ = 6800 000 N/m) **[5], [6]**.

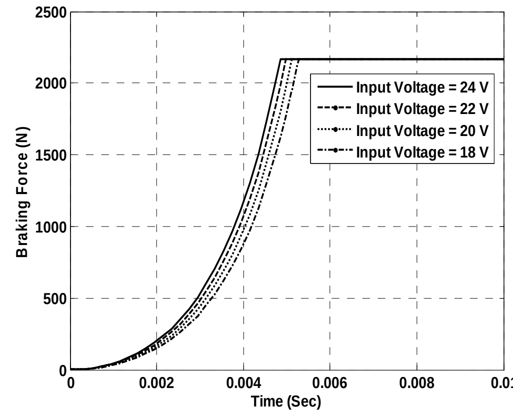

Figure (8): Influence of input voltage (V_{IN}) on braking force (F_B)

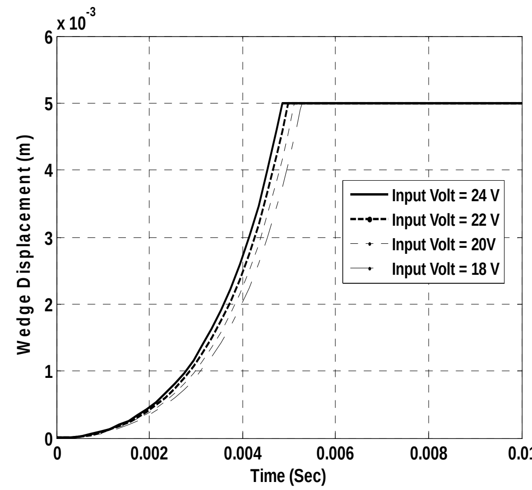

Figure (9): Influence of input voltage (V_{IN}) on wedge displacement (X_W)

From braking force and wedge displacement curves it is clear that as the input Voltage (V_{IN}) increases, the output braking force (F_B) increases as well and the wedge displacement (X_W). In another words, the displacement will go to the stop end faster comparing with another displacement values for a lower input voltages.

ii. The Wedge Angle (α)

In this model the input will be the wedge angle (α), it will have three different values 8º, 12º and 15º. Other parameters will be constant inputs in this model (the Input voltage V_{IN} = 24 V, the wedge mass M_W= 0.3 Kg, the coefficient of friction μ = 0.3, and the caliper stiffness $K_{CALLIPER}$= 6800 000 N/m).

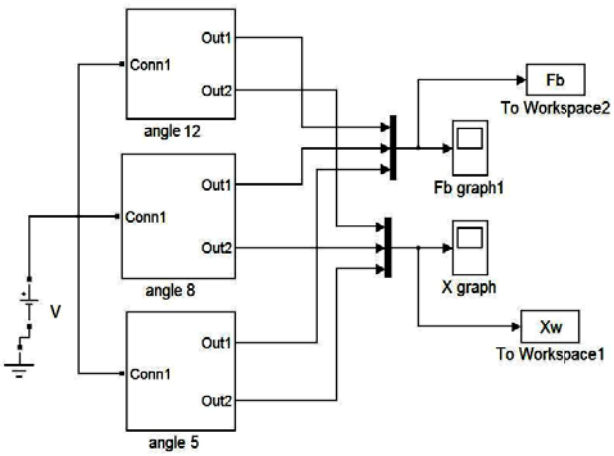

Figure (10): SIMULINK model of the system with wedge angle (α) as system input and braking Force (F_B) and wedge displacement (X_W) as system outputs

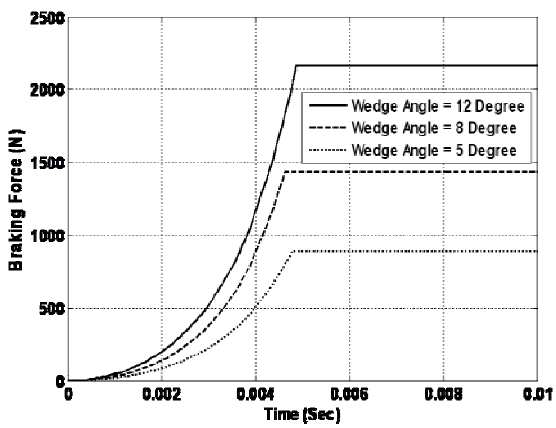

Figure (11): Influence of the wedge angle (α) on the braking force (F_B)

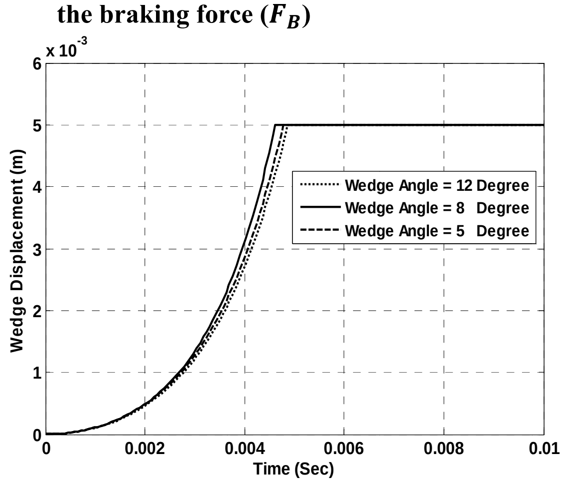

Figure (12): Influence of the wedge angle (α) on wedge displacement (X_W)

As the wedge angle increases the clearance between the wedge and the caliper decreases; in case of large wedge angle the movement of the roller screw will transfer quickly to the pads to generate the braking force (F_B).

So we can conclude from the output curves that as the wedge angle increases, the braking force increases and the wedge displacement has a higher value and goes to the stop end faster than the displacement of the other lower wedge angles values.

iii. Coefficient of Friction (μ)

In this model the input will be the coefficient of friction (μ) it will have three different values 0.3, 0.4 and 0.5. Other parameters will be constant inputs in this model (the Input voltage V_{IN} = 24 V, the wedge mass M_W = 0.3 Kg, the wedge angle α = 12 º and the caliper stiffness $K_{CALLIPER}$ = 6800 000 N/m).

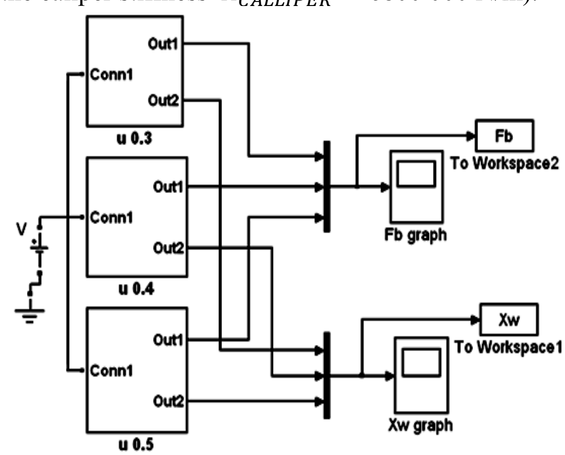

Figure (13): The SIMULINK model of the system with the Coefficient of friction (μ) as system input, the system output will be the Braking Force (F_B) and Wedge Displacement (X_W).

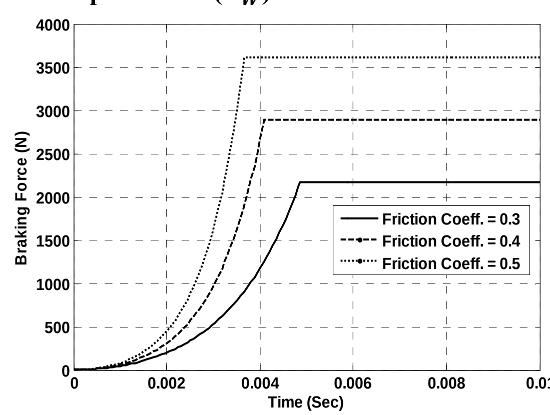

Figure (14): Illustrates the influence of the Coefficient of friction (μ) on the Braking Force (F_B).

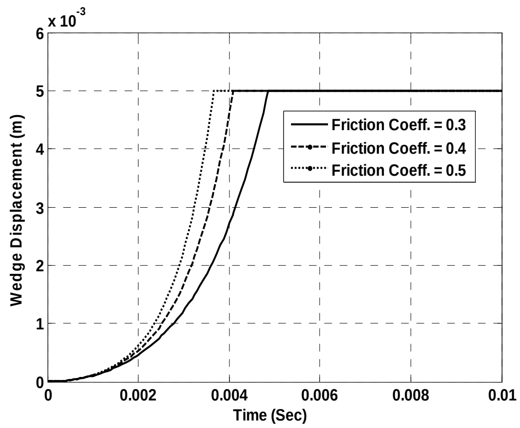

Figure (15): Illustrates the influence of the Coefficient of friction (μ) on Wedge Displacement (X_W).

As the coefficient of friction between the brake pads and the brake disks increase, it helps to build up the braking force quickly and by this the wedge displacement will decrease.

We can conclude that as the coefficient of friction increases the braking force increases and the wedge displacement has a higher value and goes to stop end faster than the other lower wedge angles values.

Conclusions

This present paper has investigated the effect of design parameters of self reinforcement brake system on its performance.

A mathematical model including a DC motor, roller screw has been used to simulate the full self reinforcement brake system. Different input variables that directly affect the system performance (such as input voltage, wedge angle, coefficient of friction) have been used in the mathematical model. The results of the output parameters which are the wedge displacement and the braking force are presented.

The results show that as the coefficient of friction, the wedge angle, and input voltage increase the braking force and the wedge displacement increase, and as the wedge angle increases the wedge goes to the stop end faster. Increase of the braking force and faster reach of wedge to the stop end would improve the brakes performance by shortening the brake distance and the time of braking.

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