

A dynamic model of electronic wedge brake: experimental, control and optimization

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Article Info

Article history:

Received Apr 23, 2021

Revised May 18, 2021

Accepted May 19, 2021

Keywords:

Brake-by-wire

Electronic wedge brake

EWB mathematical model

Self energize brake

Wedge brake system

ABSTRACT

This paper discusses the process of modelling and parameter selection for the creation of the electronic wedge brake system (EWB). The system involves a permanent magnet DC engine (PMDC) that drives the motor, the gear leadscrew, and the brake core. The proposed model is simpler and more flexible which can be used in both the most well-known EWB designs either natural or optimized EWB. The selection of the motor is rendered according to the brake specifications. The wedge angle profile is centred on the derivation of EWB system that consists of brake actuator, wedge mechanism dynamic, and wedge characteristic brake factor. Control and optimization are carried out with specific coefficients of friction of the brake pads to maintain operating reliability. A 5th-order brake simulation model of the EWB in a single state-space was derived and a simulation was conducted to verify the distribution of force. The efficiency of the brake clamping force control system was assessed by proportional-integral-derivative (PID) control. The performance of the proposed controller is verified in simulations and experiments using a prototype electronic wedge brake. The research findings indicate, the actuator restriction is deemed to achieve consistent performance against full range braking during the EWB control design.

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1. INTRODUCTION

There is a clear trend in the automotive industry today towards power-by-wire technologies designed to replace hydraulic or pneumatic systems with comparable electrically powered ones. Recently, electronic wedge brake (EWB) received attention for introducing "brake -by -wire" solutions. Various EWB prototypes were first introduced by the German aerospace center (eStop@-GMBH) [1] and are widely reported in the literature review. It begins from a single motor [1] to a double motor [2], [3] and then returns to a single motor [4]-[12] to mechanically minimize the backlash. The optimized EWB version was introduced to increase EWB brake efficiency [8]. To this end, the angle of the engine's actuation during the mechanical design should be set equal to the angle of the coil. To this end, the angle of the engine's actuation during the mechanical design should be set equal to the angle of the wedge. Based on this basis, several attempts have been made by researchers based on this design concept [5], [13]-[18].

The findings largely confirm that the use of a wedge in an electromechanical brake mechanism can dramatically reduce the necessary actuating forces and thus allow the development of much more sophisticated systems for automotive applications. Nevertheless, for the application, which the regulation of the EWB mechanism, it is noted that to achieve the highest level of fidelity protection there is still a significant barrier and downside [19]. Some of the obtained experimental results suggested several delays in the response signal and did not comply with the related theories. Upon analysis, it focuses on the less accurate prediction of the EWB system during the modelling phase, the simplification, idealization, and simulation methodology used during brake system modelling, and yet it is a critical piece of information which determines the brake system's capabilities. As stated in [20], one of the key factors for achieving desirable control efficiency is the provision of an effective system model that can accurately simulate the system's dynamic behaviour. To date, the EWB framework has two popular methods of dynamic modelling, namely physical modelling (PM) and system identification (SI) methods. These two approaches are very useful in creating a mathematical model for the unit.

However, these methods do have advantages and drawbacks. The SIM technique can generate simulations of the exact responses that are true to the system mechanism [21]. Nonetheless, this model may not be appropriate for other systems. On the other hand, the developed model may be reused for other systems with the same mechanism in the case of PM techniques, but some adjustment of the parameters according to the mechanism of development is needed. In general, based on PM techniques, the dynamic EWB model was derived from the ordinary differential equation (ODE) by dividing the entire EWB system into three subassembly parts: DC-motor, Lead Screw and EWB-Brake Heart [8], [9], [11], [22]. So, these validated models are acceptable, and later contributed to the use of researchers. Even so, in these equations, there are disadvantages where the derivations have not ended with state-space or transfer function, form, and thus make it less reliable to use for control design. The implementation of a full EWB model based on 5 by 5 state space representation [22] surmounted these weaknesses.

It is noted that the EWB mechanism contains nonlinearities and variable parameters in its components which can also affect system performance, such as the efficiency of the lead screw or roller screw and the friction coefficient of the brake pad. The efficiency of the roller and the lead screw will depend on the translational variable, whether it acts as a driver or guide to the rotating part, whereas the pad's coefficient of friction increases proportionally to the pad's surface temperature and decreases the presence of water [23], [24] and water [25]. Otherwise the pad friction also has a nonlinearity of low disk speed which can be expressed with the sigmoid function [23]. Numerous researchers have tried a variety of methods to address these problems. However, the definitive way to solve this problem has yet to be found. In order to contribute to the advancement of the EWB, a complete model of an integrated EWB system using the PM method has been developed in this study. The objectives are deriving mathematical equation for PMDC for EWB, identify the effect of actuation angle, experimentally validate the model, and finally performed performance analysis of the EWB using PID controller.

There are four sections in this article. The first segment focuses on the implementation of the EWB and the review of other relevant work. The complete mathematical modelling of the optimized EWB is then defined, followed by the design section for the required goal, engine selection, and experimental validation of engine and EWB parameters. The PID controller-based clamping force controller is designed to simulate the model and the simulation result is addressed. PID parameters are tuned dependent on optimization-based tuning. Finally, the conclusion and the potential work plan are mixed in the last section.

2. MATHEMATICAL MODEL OF EWB

In order to develop the EWB's suitable mathematical modelling a clear understanding of the EWB process is required to provide better insight. The development of the EWB's mathematical equation is proposed in this section and will be explained on the basis of physical modelling. Subdividing the brake system into several different assemblies is useful for modelling purposes. These can be implemented within the overall model as separate subroutines or blocks, as shown in Figure 1. The brake model is divided into two main parts, the brake actuator, and the heart-brake mechanism. As shown in Figure 1, The brake actuator consisted of two components: the DC motor and the roller screw. The DC motor actuator is used in this system to move the input torque and force the centre brake through a roller screw, which transforms the angular motion of the DC motor into the axial motion of the coil in the centre of the brake. On the other hand, the heart of the brake, consisting of a wedge mechanism, a calliper, and a brake pad, may have diagonal motions, providing a clamping force to the brake disk.

2.2. Wedge mechanism dynamic

Consider the EWB with the angle of the motor shaft, β as in Figure 1. The relationship between the wedge actuation forces (F_m), reaction forces (F_r), and clamping forces (F_c) to the disc are derived based on force balance as follow:

The dynamic of a wedge in x-direction:

$$F_m \cos \beta + \mu F_c - F_r \sin \alpha = M_w \dot{V}_w \tag{6}$$

By dividing with $\tan \alpha$, the new form of (7) can be described as follow:

$$F_r \cos \alpha = \frac{F_m \cos \beta + \mu F_c - M_w \dot{V}_w}{\tan \alpha} \tag{7}$$

Besides that, the dynamic of a wedge in y-direction stated as:

$$F_m \sin \beta + F_r \cos \alpha - F_c = M_w \dot{V}_w \tan \alpha \tag{8}$$

where M_w and V_w are wedge mass and wedge velocity in x-direction, respectively. Substitute the (7) into (8), then rearrange will be produced.

$$\dot{V}_w = \frac{F_m(\mu - \tan \alpha)}{M_w(\tan^2 \alpha + 1)} + \frac{F_m(\sin \beta \tan \alpha + \cos \beta)}{M_w(\tan^2 \alpha + 1)} \tag{9}$$

From (9), we are interested in simplifying the complex multiplier formula of motor force (F_m) which is a function of the motor actuation angle and the wedge angle $f(\beta, \alpha)$. To achieve optimum multiplication of the brake factor, the motor shaft angle should have the same angle as the wedge angle instead of a zero angle as on a normal EWB. Assuming the two angles are equal, this function can be summarized as follows,

$$f(\beta, \alpha) = \cos \beta + \sin \beta \tan \beta$$

$$f(\beta, \alpha) = \frac{1}{\cos \beta}$$

Thus, the simplified wedge dynamic model can be described as:

$$\dot{V}_w = \frac{1}{M_w(\tan^2 \alpha + 1)} \left[F_c(\mu - \tan \alpha) + \frac{F_m}{\cos \beta} \right] \tag{10}$$

Meanwhile, the clamping force depends on the calliper stiffness (K_{cal}), wedge displacement, and wedge angle.

$$F_c = K_{cal} X_w \tan \alpha \tag{11}$$

Substitute (11) into (12) then produce,

$$\dot{V}_w = \left[\frac{K_{cal} \tan \alpha (\mu - \tan \alpha)}{M_w(\tan^2 \alpha + 1)} \right] X_w + \left[\frac{1}{M_w(\tan^2 \alpha + 1) \cos \beta} \right] F_m \tag{12}$$

Where:

$$\beta = \begin{cases} 0 & , \text{for Normal EWB} \\ \alpha & , \text{for Optimized EWB} \end{cases}$$

2.3. Wedge brake factor

The EWB braking factor plays an important role in enlarging the ratio of braking force versus actuator force. In contrast to the conventional braking factor, the wedge-based brake system will increase several times the braking factor due to the self-energizing effect. In steady state condition, in (10) can be simplified as follows:

$$F_c(\mu - \tan \alpha) + \frac{F_m}{\cos \beta} = 0 \quad (13)$$

a pair of brake pads installed each wheel disk generate double brake force. Thus, relation between braking forces and clamping forces is stated as,

$$F_c = \frac{F_b}{2\mu} \quad (14)$$

Substituting (14) to (13), and then rearranging the equation will produce a wedge characteristic brake factor, C^* :

$$C^* = \frac{F_b}{F_m} = \frac{2\mu}{\tan \alpha - \mu} \left(\frac{1}{\cos \beta} \right) \quad (15)$$

where:

$$\beta = \begin{cases} 0 & , \text{for Normal EWB} \\ \alpha & , \text{for Optimized EWB} \end{cases}$$

Based on (15), we can realize that although the actuator angle (β) should be set equal to the wedge angle (α) to obtain optimum amplification of the braking factor, the amount of additional amplification in the EWB varies according to the angle of the actuator. The additional amplification value increase as angle of wedge increase. Furthermore, the efficiency of the personalized EWB can be calculated using (15). By using the recommended wedge angle spacing for standard coefficient of friction brake pads, which is approximately 25 to 43 degrees [28], the optimized EWB increases the braking factor from 10.3 to 36.7 percent compared to the normal EWB. As shown in Table 1, the (15) developed to represent the characteristic brake factor is simpler and slightly differs from other researchers. Many researchers multiply the equation by two, as each wheel uses a double brake pad. The researchers still underestimate the wedge friction coefficient (μ_w) but are considered in [28].

Table 1. Brake factor formula representation by researchers

Source	Equation of characteristic brake factor of optimized EWB
Year 2007, Fox <i>et al.</i> [8],	$\frac{2\mu}{\tan \alpha - \mu} (\cos \beta + \sin \beta \tan \alpha)$
Year 2013, Park <i>et al.</i> [29]	
Year 2015, Shin <i>et al.</i> [13]	
Year 2017, Wang <i>et al.</i> [28]	$\frac{\mu}{\tan \alpha - \mu} \times \frac{\cos(\alpha - \beta)}{\cos \alpha}$
This article	$\frac{\cos \alpha (\tan \alpha - \mu) + \mu_w \cos \alpha + \mu_w \mu \sin \alpha}{2\mu} \left(\frac{1}{\cos \beta} \right)$

2.4. Proposed complete EWB model

The entire EWB model can be obtained by combining all the mathematical differential equations, as discussed previously in a separate component. There are 5 states available, which are wedge distance (X_w), wedge velocity (V_w), motor angle (θ_m), angular motor velocity (ω_m), and motor current (I_m). Substitute (5) for the dynamic wedge from the axial lead screw to (12).

$$\dot{V}_w = \left[\frac{K_{cal} \tan \alpha (\mu - \tan \alpha) - K_a / \cos^2 \beta}{M_w (\tan^2 \alpha + 1)} \right] X_w + \left[-\frac{D_a}{M_w (\tan^2 \alpha + 1) \cos^2 \beta} \right] V_w + \left[\frac{K_a L_a N_a / 2\pi}{M_w (\tan^2 \alpha + 1) \cos \beta} \right] \theta_m + \left[\frac{D_a L_a N_a / 2\pi}{M_w (\tan^2 \alpha + 1) \cos \beta} \right] \dot{\theta}_m \quad (16)$$

By substitute (3) for lead screw into (2) from PMDC Motor mechanical equation, then rearrange it as,

$$\dot{\omega}_m = \left[\frac{L_a N_a K_a}{2\pi \eta J_m \cos \beta} \right] X_w + \left[\frac{L_a N_a D_a}{2\pi \eta J_m \cos \beta} \right] V_w + \left[-\frac{(L_a N_a)^2 K_a}{4\pi^2 \eta J_m} \right] \theta_m + \left[-\frac{(L_a N_a)^2 D_a}{4\pi^2 \eta J_m} - \frac{D_m}{J_m} \right] \omega_m + \left[\frac{K_t}{J_m} \right] I_m \quad (17)$$

The (1) from PMDC Motor electrical equation can be rearranged as follow,

$$I_m = \left[-\frac{K_e}{L_m}\right] \omega_m + \left[-\frac{R_m}{L_m}\right] I_m + \left[\frac{1}{L_m}\right] V_m \tag{18}$$

The complete EWB actuator model representing the combination of the engine, the lead screw with the gear and the EWB (brake heart) mechanism is finally derived from this. Final differential (16), (17) and (18) may be depicted for the form in the fifth-order linear state space:

$$\begin{cases} \dot{X} = Ax + Bu \\ y = Cx + Du \\ x = [X_w, V_w, \theta_m, \omega_m, I_m]^T \\ y = F_c \end{cases} \tag{19}$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -\frac{K_a - a_1 a_4^2}{a_2 a_4^2} & -\frac{D_a}{a_2 a_4^2} & \frac{K_a a_3}{a_2 a_4} & \frac{D_a a_3}{a_2 a_4} & 0 \\ 0 & 0 & 0 & 1 & 0 \\ \frac{K_a a_3}{\eta J_m a_4} & \frac{D_a a_3}{\eta J_m a_4} & -\frac{K_a a_3^2}{\eta J_m} & -\frac{D_m}{J_m} - \frac{D_a a_3^2}{\eta J_m} & \frac{K_t}{J_m} \\ 0 & 0 & 0 & -\frac{K_e}{L_m} & -\frac{R_m}{L_m} \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \frac{1}{L_m} \end{bmatrix}, \text{ and } C = \begin{bmatrix} K_{cal} \tan(\alpha) \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}^T \tag{20}$$

where

$$\begin{aligned} a_1 &= K_{cal} \tan \alpha (\tan \alpha - \mu) \\ a_2 &= M_w (\tan^2 \alpha + 1) \\ a_3 &= \frac{L_a N_a}{2\pi} \\ a_4 &= \cos \beta, \\ \beta &= \begin{cases} 0 & , \text{for Normal Actuation EWB} \\ \alpha & , \text{for Optimized Actuation EWB} \end{cases} \end{aligned}$$

3. MODEL VALIDATION

3.1. Brake requirement

Several specifications were laid out in this study to define the optimum braking force in the design of the EWB. The objective is to develop an EWB system for the use of medium sized passenger vehicles in the B-segment as in [30]. The effective braking force generated by the electronic wedge brake depends primarily on the angle of the wedge. Determination of the optimum wedge angle is therefore critical in the design of the electronic wedge brake. Since the angle of the wedge depends on the coefficient of friction of the brake pad, priority should be given to selecting the brake pad. The angle of the wedge and the selection of the brake pad are two critical factors to produce a higher braking force and to avoid the possibility of the wedge sticking. Therefore, in this study, a brake pad type FF (SAE Code) with a friction coefficient ranging from 0.35 to 0.45 was selected for use in the design of the EWB. Based on the coefficient of the brake pad, the optimization was performed and the optimum wedge for the wedge function was found to be 24.5 degrees.

By substituting the wedge angle and the pad coefficient value for (15), the brake factor of the selected wedge angle may be tested. A brake factor of around 7.276 can be produced with a pad coefficient of 0.35. If β is not entered in the equation (normal EWB) only 6.621 will be produced for the same parameter otherwise. Self-reinforcement at the maximum value will be at a friction coefficient of 0.45, so no motor force is required. When the pad coefficient exceeds this value, however, it is very difficult to control, because the brake factor is very high. In addition, it is checked using the same equation that only 982.96 N motor power is required to produce a maximum braking force of 7152 N.

In addition, the necessary engine torque can be examined by consuming (4). Here, it is set that L_a is 3 mm, that η is 0.65, and that N_a is 1. Noted, the F_m . It is equivalent to 982.96 N, which has already been calculated. The torque generated by this measurement is 0.7220 Nm. Otherwise, (20) can be used to obtain the required engine speed. This equation assumes that the load generated by the wedge movement is linear.

$$RPM_{target} = \frac{60 * G_w}{L_a \tau \tan \alpha} \tag{20}$$

The equation as the G_w is a wedge travelling distance at the average braking force from the rest position to the maximum displacement, which is the goal time to reach. The distance between the pad and the disk is set at 0.5 mm (gapping mode), and the maximum displacement during brake operation is 0.5 mm (clamping mode). The target time for achieving maximum brake force is set at 0.2 s. The maximum engine speed achieved by the target RPM is 219.43 RPM, based on these parameters.

Engine selection was made by reference to the parameters calculated. It is determined that Xiangyi Enterprise Co., Ltd 's DC carbon-brush engine model IG-420024X with a rated torque of 0.98 NM at 248 RPM is suitable for design requirements. Noted the engine had a power rating at 41.3 W and can vary according to torque and set rpm. This choice of engine is rational since about 60W of input power is currently used in [27] to stop the vehicle at demand of 950 Nm, while another researcher is using less than 50 W to stop 2000 kg of the vehicle [7].

3.2. Controller design

The EWB controller is performed to verify system performance based on the requirement of target design and to ensure the efficiency of the previous motor selection procedure. Using the MATLAB control system designer tool, the proportional-integral-derivative (PID) tuned gradient-descent-active-set algorithm optimisation method. The proper tuning based on SISO-Optimization technique [31], [32] is used to reduce response time to the minimum level.

The optimization is performed based on a design requirement depending on an overshoot of 5 per cent, an increase of 0.2 s, and an actuator saturation limit of 0.0012 V for the reference unit step. The PMDC engine used receives an input voltage of up to 12 V, and the maximum braking force at each front wheel is 7.152 N. Thus, the maximum clamping force required by dividing it with the brake pad coefficient is 10,217 N. The actuator saturation shall be considered to sustain the brake force controller output from the minimum to the maximum braking force requirements for a wide working envelope.

Due to the existing constraint rule solution set during optimisation, the design criterion was re-adjusted at an optimum level. Based on this analysis, the parameters of the PID controller, which is the proportional gain, K_p , are obtained. It is 0.000289, integral gain, K_i . It is 0.000606. The derivative gain, K_d . It is 2.97×10^{-5} , and the time constant of the derivative first-order filter, T_f . It is 0.0325.

4. EXPERIMENTAL VALIDATION AND EWB PARAMETERS

Since all 6 DC motor parameters are not directly informed, the engine performance during no-load and the average load available on the datasheet are used as a guide to the engine parameters obtained. However, by solving motor mathematical modelling on (1) and (2) with datasheet information, only 4 parameters can be obtained. Using the MATLAB software, two other parameters are obtained, engine inertia and inductance, by evaluating the physical motor via system identification. The engine encoder's motor location signal is connected to the PC via the NI-PCI-6221 DAQ card. To obtain two additional motor parameters, the approximate transfer function model obtained is then replaced with another 4 available parameters. Based on these parameters the engine characteristics graph is produced to be validated with the engine data sheet as in Figure 2.

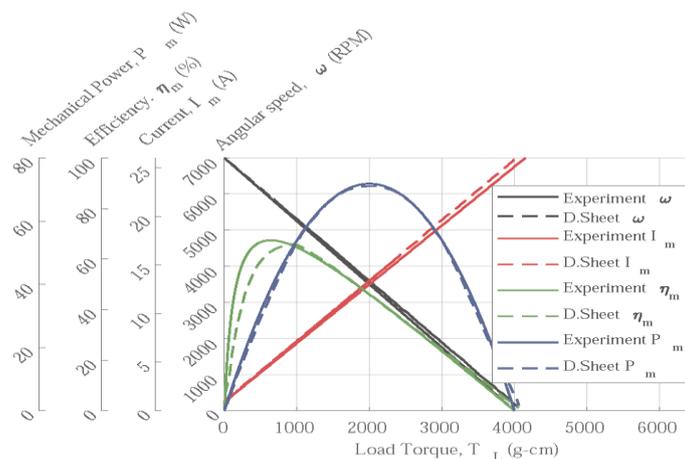


Figure 2. PMDC motor characteristics based on experimental data and IG-420024X graph datasheet

As illustrated in Figure 2. The parameters obtained in the previous method are true because the trend and the value of the graph obtained are identical to the trend shown in the datasheet of the supplier. Several parameters are obtained to test the complete EWB model, based on physical parameters such as selected DC motor, brake pad, and wedge parameters, and others taken from research papers as mentioned in the previous discussion. Because the EWB prototype still under production, those specifications have not yet been finalized. Table 2 lists all parameters used for this research.

Table 2. EWB DC carbon-brush motor model IG-420024X parameters

No	Parameter, Symbol	Value (Unit)
1	Motor Resistance, R_m	0.4781 Ω
2	Motor Inductance, L_m	0.0230 H
3	Electromotive Force Constant, K_e	0.0158 N.m/A
4	Torque constant, K_t	0.0156 N.m/A
5	Motor moment inertia, J_m	7.094×10^{-3} Kg.m ² /s ²
6	Motor viscous friction constant, D_m	1.9175×10^{-5} N.m.s
7	Gear Reduction, N_a	1/24
8	Axial stiffness, K_a	750e6 N/m
9	Axial viscous friction constant, D_a	9.3279×10^{-5}
10	Lead Screw efficiency, η	0.63
11	Lead Screw Pitch, L_a	3 mm
12	Wedge Weight, M_w	0.3 Kg
13	Wedge Angle, α	24.5 degree
14	Motor axial angle, β	24.5 degree
15	Calliper stiffness, K_{cal}	44.8385×10^6 N/m
16	Brake pad coefficient, μ	0.35

5. RESULTS AND DISCUSSION

This stage is designed to ensure engine selection and other EWB parameters follow design requirements. For this reason, the brake clamping force control system is designed. A series of tests were performed to investigate the performance of the system for the entire operating envelope, i.e., from low to maximum brake clamping force as shown in Figure 3. It shows that the designed controller met the performance requirements for a series of step commands. The main key to consistency in performance is due to the saturation of the actuator consideration during system design.

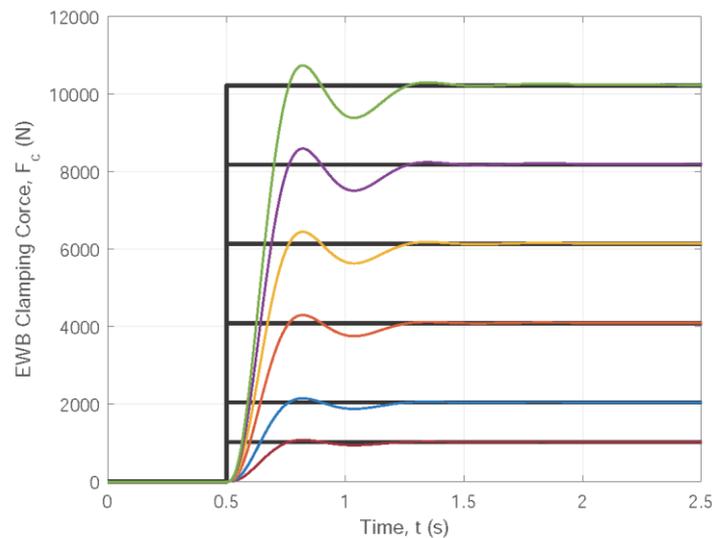


Figure 3. PID based EWB brake clamping force response to force step commands of 10%, 20%, 40%, 60%, 80% and 100% from maximum 10,217 N force demand

The investigation of designed system behaviour is further evaluated during step input tracking with maximum clamping force of 10,217 N as in Figure 4.

As in Figure 4(a), at maximum force demand, the overshoot, rise time and settling time were 5.08 per cent, 0.16 seconds, and 0.70 seconds, respectively, with zero steady state error. Meanwhile the controller working within actuator limit as shown in Figure 4(a) at second axes. The controller output achieves the design specification goal set. It has demonstrated the effectiveness of the engine selection method used earlier. Figure 4(b) shows that the wedge position at a maximum displacement of 0.5 mm at the maximum brake clamping force and the small bit vibration occurs at the wedge before the wedge is settled. The engine angular velocity peak value is also 160.9 rad/s, which is far from a maximum engine speed of 733 rad/s. Furthermore, another 3 states of the EWB model that represent PMDC motor behaviour during closed-loop for maximum braking demand are observed and shown in Figure 5.

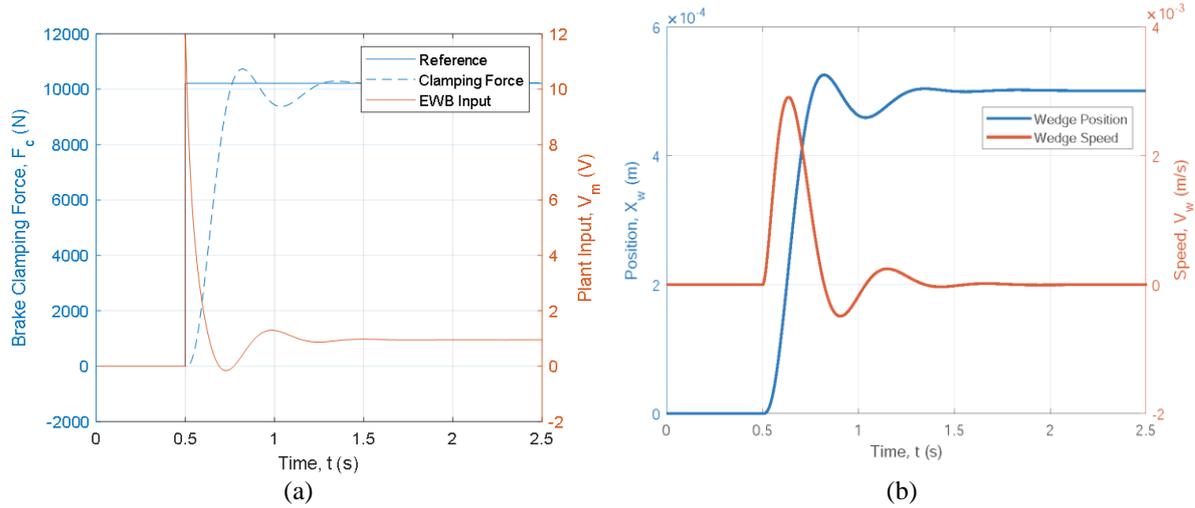


Figure 4. System behaviour at maximum demand; (a) clamping force and actuator effort and (b) wedge position and speed states responses

As Figure 5(a), the wedge and motor reaction are almost a similar pattern for both position and speed and can be further investigated. The actuator current present is 9.5 A, as in Figure 5(b) just below the engine level. Note that this simulation does not include travel time from the brake pad resting state until the pad and disc meet each other.

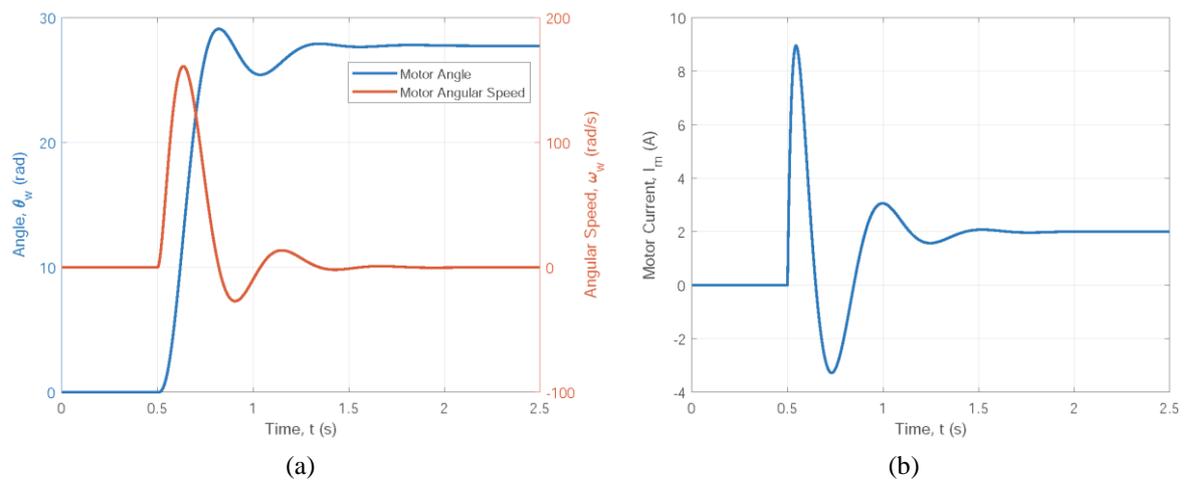


Figure 5. PMDC motor behaviour at maximum demand; (a) Motor angle and angular speed states responses and (b) motor current state response

6. CONCLUSION

The mathematical equations for the complete EWB model have been produced and optimized. The model is more compact and simpler compared to the various versions of EWB that researchers have used before. Moreover, it is very flexible so that it can be applied to both well-known designs which are activated and optimized activation versions. The activation angle effect is identified where the EWB brake factor can reach up to 36.7 per cent depending on the selection of the brake pads and wedge angle design. The PMDC drive model used in producing an EWB has been experimentally validated with results that are very similar to the performance datasheets from the manufacturer. Performance analysis for the designed EWB was performed using a PID controller. The results show that the designed model can perform very well in accordance with the requirements of the system.

ACKNOWLEDGEMENTS

The authors would like to thank Universiti Teknikal Malaysia Melaka (UTeM) for the Short Term Research University Grant PJP/2020/FKM/PP/S01783, and the Faculty of Engineering, Universiti Putra Malaysia (UPM) for providing the facilities and conducive learning environment in conducting the research.

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