

High-Bandwidth Clamp Force Control for an Electromechanical Brake

Chih Feng Lee and Chris Manzie
 The University of Melbourne

ABSTRACT

A controller that fully utilizes the available motor capacity of an electromechanical brake to achieve high closed-loop bandwidth is proposed. The controller is developed based on the time-optimal switching curve derived from Pontryagin's Maximum Principle. The control input is scheduled using a switching surface based on the current motor velocity and position offset. Robustness to modeling errors is achieved by introducing a boundary layer in vicinity of the switching curve, reminiscent of a high gain controller. A flexible tuning procedure is also developed to aid in practical implementation, allowing a balanced choice between tracking speed and energy usage. The controller is implemented on a production-ready prototype EMB, and tested over different braking scenarios to assess the performance and robustness relative to the benchmark controllers. It is demonstrated that significant improvements in step response and dynamic tracking are obtained using the proposed approach.

CITATION: Lee, C. and Manzie, C., "High-Bandwidth Clamp Force Control for an Electromechanical Brake," *SAE Int. J. Passeng. Cars - Electron. Electr. Syst.* 5(2):2012, doi:10.4271/2012-01-1799.

INTRODUCTION

Compared with traditional hydraulic alternatives, brake-by-wire (BBW) technology offers reductions in components, space requirements, environmental impact, and increased design flexibility through software upgrades. Currently there are two implementations of BBW actuation, differentiated by the availability of self-reinforcement braking mechanisms. Electromechanical brakes (EMBs) are commonly used to identify those designs without self-reinforcement braking, while electronic wedge brakes (EWBs) denote actuators with self-reinforcement braking. Clamping force generation in EMBs and EWBs is facilitated by one or multiple electric motors, connected through a reduction mechanism to the brake pads. The control problem dealt with in this work is the clamp force feedback control in EMB, which directly correlates to the servo control of the brake piston position. It is noted that this problem is closely related to the EWB force control problem that manipulates the wedge position.

From a performance perspective, EMBs and EWBs potentially offer finer clamp force control actuation with high closed-loop bandwidth relative to hydraulic systems. This capability is beneficial for maintaining high performance anti-lock braking and electronic stability control. However, the clamp force control performance is dependent on the adopted control architecture and the selected gains.

Existing EMB and EWB clamp force controllers borrowed the control architecture from linear motion control applications, where cascaded proportional-integral controllers are implemented [1,2,3]. However, more so than in most motion control applications the EMB and EWB are inherently nonlinear devices, and frequently operate over the full range of operating conditions. As a consequence, high closed-loop bandwidth across the whole clamp force region is not guaranteed using this design with a fixed set of gains. Gain scheduled controllers were consequently proposed in EMB control albeit with tedious tuning procedures [4,5].

As an alternative, this paper proposes a controller design procedure that fully utilizes the available motor capacity to achieve rapid setpoint tracking performance with high closed-loop bandwidth, at the same time, offers the flexibility of detuning for energy saving considerations. The controller is developed based on the time-optimal switching curve derived from Pontryagin's Maximum Principle [6]. The control input is scheduled using a switching surface based on the current motor velocity and position offset. Robustness to modeling errors is achieved by introducing a boundary layer in vicinity of the switching curve, reminiscent of a high gain controller. A tuning procedure is developed to aid in practical implementation. The procedure is based on optimizing a function of convergence speed and control effort. A choice of

appropriate weightings on the objective function allows tradeoffs between these two conflicting metrics to be made.

The proposed controller is implemented on a production-ready prototype EMB, and tested over different braking scenarios to assess the performance and robustness relative to the benchmark controllers. It is demonstrated that significant improvements in step response and dynamic tracking are obtained using the proposed approach. Therefore, it is suggested as a candidate for future production EMB controller design.

The organization of the paper is as follows. The second section describes the control-oriented model of an EMB that serves as the basis for the proceeding controller designs. An ideal time-optimal control for an EMB is first proposed, followed by the robust near time-optimal control (NTOC). A gain tuning procedure for the NTOC will be presented, proceeded by discussions on obtaining robust performance against modeling errors and noise. Then, experimental results will be presented and discussed. The conclusion encompasses the main results and establishes further work required to take advantage of the achieved high closed-loop bandwidth.

CONTROL-ORIENTED EMB MODEL

A production-ready EMB prototype shown in [Figure 1](#) is chosen in this work to illustrate the proposed high-bandwidth clamp force control design procedure. The EMB consists of a three phase, permanent magnet synchronous motor, a gear reduction stage, a ball screw, a floating caliper and control electronics. A low order, lumped parameter model from [4] is chosen as the basis for the proposed controller design. While these simplifications facilitate the construction of a low order controller, simulations in this paper are performed using higher-order models presented in [7].

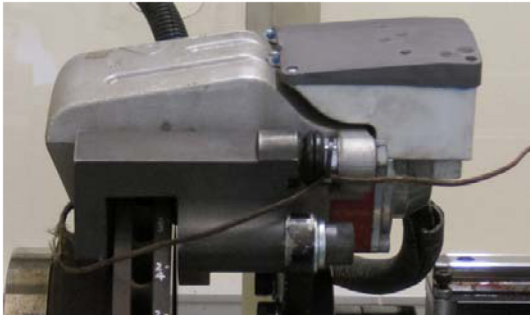


Figure 1. The production-ready prototype electromechanical brake used in this work.

The torque equation about the motor's rotational axis is given by

$$J\ddot{x}_2 = -NF_{cl}(x_1) - T_f(x_1, x_2) + T_m \quad (1)$$

where F_{cl} , J , N , T_f , T_m , x_1 , and x_2 represent brake clamp force, effective moment of inertia, gear ratio, friction torque, motor torque, motor angular position, and motor angular

velocity respectively. The motor model is approximated using an equivalent DC motor, where the torque is given by

$$T_m = K_t i_q \quad (2)$$

where i_q and K_t are the motor quadrature current and motor constant respectively. The lumped stiffness is presented as the relationship between the clamp force and motor position. It is experimentally found to be sufficiently well approximated using a third-order polynomial. Additionally, it is modeled using a first-order continuously differentiable function with respect to the motor position, a requirement for the derivation of the ideal time-optimal solution. With $x_1 = 0$ defined at the contact position between the brake pad and disk, the clamp force is represented by

$$F_{cl}(x_1) = \begin{cases} k_1 x_1^2 + k_2 x_1^3 & \text{if } x_1 \geq 0 \\ 0 & \text{if } x_1 < 0 \end{cases} \quad (3)$$

By considering Coulomb, viscous, and load-dependent sources of friction, the lumped non-linear friction torque about the motor's rotational axis is modeled as

$$T_f(x_1, x_2) = Dx_2 + (C + GF_{cl}(x_1))\tanh(\varepsilon x_2) \quad (4)$$

where the friction model parameters D , C , and G are the viscous friction coefficient, load-independent Coulomb's friction torque, and load-dependent Coulomb's friction torque coefficient respectively. The $\tanh$ function is used to approximate the Coulomb's friction in order to ensure the first-order continuous differentiability of friction torque with respect to the states, a requirement for the derivation of the ideal time-optimal solution. A sufficiently large ε is chosen such that the friction model is close to the experimentally obtained measurements. Additionally, motor torque and velocity are limited to $|T_m| \leq T_{m\max}$ and $|x_2| \leq \theta_{\max}$ respectively, while the clamp force region considered in this work is between 0 to 30 kN. The experimentally identified EMB parameters are listed in [Table 1](#).

Table 1. EMB Parameters

C	Coulomb friction torque	5.10×10^{-2} N.m
D	Viscous friction	5.12×10^{-4} N.m.s/rad
G	Friction torque coefficient	2.52×10^{-5} N.m/N
N	Gear ratio	2.63×10^{-5} m/rad
J	Moment of inertia	2.91×10^{-4} kg.m ²
K_t	Motor torque constant	4.65×10^{-2} N.m/A
k_1	Stiffness coefficient	2.15×10 N/rad ²
k_2	Stiffness coefficient	-1.32×10^{-1} N/rad ³
$i_{q\max}$	Motor current limit	64.5 A
$\theta_{\max}$	Motor velocity limit	300 rad/s
$T_{m\max}$	Motor torque limit	3 Nm

A wide range of BBW actuators can be approximated using the lumped parameter control-oriented EMB model (1).

which will be utilized for the controller design presented in the following section.

CONTROLLER DESIGN

In this section, an idealized time-optimal control design is first illustrated, which provides the theoretical upper-bound limit for rapid clamp force reference tracking. However, this controller is impractical for implementation, and leads to chatter during operation due to modeling errors and measurement noise. The robust near-time-optimal control (NTOC) structure is then proposed to eliminate chatter while facilitating fast tracking response. Finally, tuning guidelines are provided to assist the design, followed by a discussion on the choice of tuning parameters.

Idealized Time-Optimal Control

High performance BBW actuators are capable of tracking the clamp force reference in minimum time, given the power rating and velocity limits of the drive. A fast clamp force tracking response is important, especially during safety-critical operations, such as ABS. Henceforth, time-optimality is a natural control performance metric.

The idealized time-optimal clamp force tracking solution can be derived from Pontryagin's Maximum Principle [6] and determined numerically, which consists of two intervals of maximum acceleration and deceleration, and possibly an intermediate interval with constant maximum velocity. Figure 2 illustrates the two different step responses for 0.8 kN and 4 kN. Beginning at $t = 0$ when $x_1 = x_2 = 0$, a clamp force setpoint reference is commanded, demanding the clamp force and motor velocity to reach the target states, which are the commanded clamp force reference and zero velocity respectively in minimum time. The time-optimal transient consists of maximum initial acceleration, operation at maximum speed and controlled deceleration to the prescribed target point, as illustrated in the 4 kN step response. The motor torque trajectory demonstrates the control switching to initiate the maximum acceleration, to maintain constant speed (from 0.03 to 0.05 seconds), and to start the maximum deceleration. Control chatter is observable during the constant speed region, as maintaining velocity at perfectly constant is not possible due to modeling and numerical errors during simulation, and discrepancies arise from modeling, measurement and discretization in experiments. In the state plane, the intervals of maximum acceleration and deceleration are characterized by arcs, while the interval at constant velocity is portrayed by a straight line parallel to the horizontal axis. For a small step response, as depicted by the 0.8 kN case, the maximum velocity may not be reached. The acceleration is immediately followed by deceleration with the switch-over taking place at fractions of the distance traveled. Notably, control chatter occurs for both the large and small step commands when the references are reached. This is due to modeling, numerical and measurement errors, which also signifies the sensitivity of the idealized time-optimal control

on these factors. During experimentation, it was observed that chatter led to overheating of the power electronics. Furthermore, it is also expected that chatter could lead to excessive mechanical wear and component fatigue failures, therefore should be avoided.

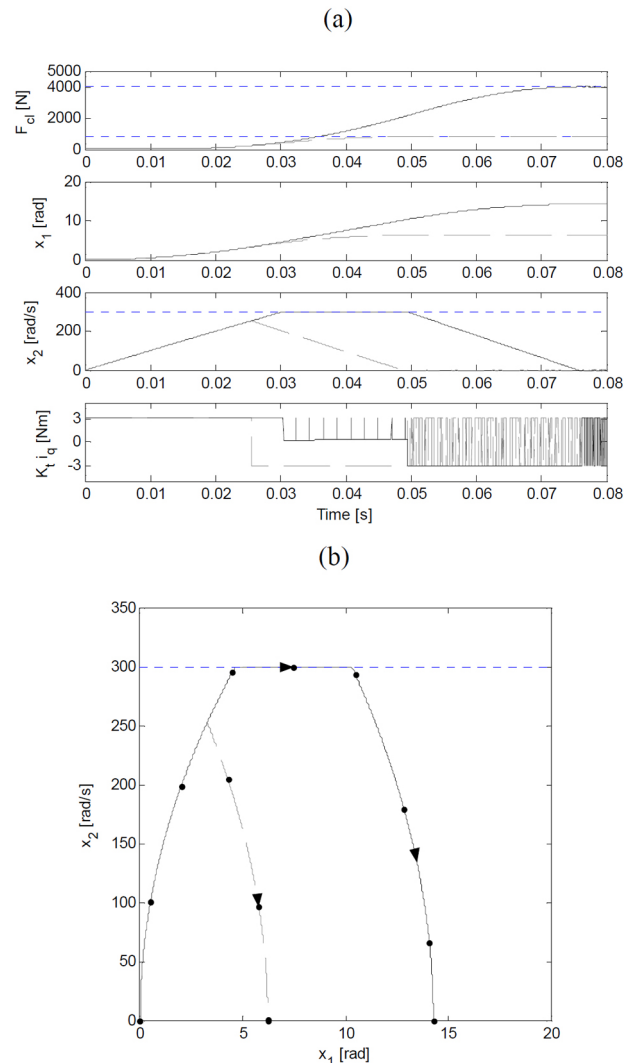


Figure 2. Time-optimal clamp force setpoint tracking for 800 N (dashed) and 4000 N (solid) with constrained motor torque and velocity: (a) Response vs. time; (b) State plane, where the dots mark the 0.01 seconds intermissions.

To aid in real-time implementation, it is beneficial to compute the time-optimal solution offline and store the control switching instants in a lookup table referred to as a switching curve.

Construction of Switching Curve

As eluded before, there can be at most one segment of maximum acceleration or deceleration that leads to the final state. If the final state is given, the terminal segment can be calculated by solving the equation of motion (1) backwards in time, which is attainable by solving the following nested