Real-Time Clamp Force Measurement in Electromechanical Brake Calipers

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Abstract—In brake-by-wire systems, central controllers require accurate information about the clamp force between the brake pad and the disc as a function of pad displacement, which is usually denoted as the characteristic curve of the caliper. Due to aging, temperature, and other environmental variations, caliper characteristic curves vary with time. Therefore, automatic caliper calibration in real-time is vital for high-performance braking action and vehicle safety. Due to memory and processing-power limitations, the calibration technique should be memory efficient and of low computational complexity. In a typical electromechanical-braking-system design, clamp force measurement variations with actuator displacement is hysteretic. This paper introduces a simple and memory-efficient real-time calibration technique in which a clamp-force model is fitted to the data samples around each hysteresis cycle. The model includes a Maxwell-slip model for the hysteresis caused by friction. Experimental results from the data recorded in various temperatures show that the proposed technique results in clamp force measurements with less than 0.7% error over the range of clamp-force variations. It is also shown that, by using these measurements, the characteristic curve can be accurately calibrated in real-time.

Index Terms—Brake-by-wire (BBW), braking, calibration, force sensing, hysteresis.

I. INTRODUCTION

RIVE-BY-WIRE is a relatively new technology in the automotive industry, which replaces traditional mechanical and hydraulic linkages with electric actuators and computer control systems. Major vehicle manufacturers in the world currently have research or collaborative development programs focused in this area. The requirements for reliability and safety in drive-by-wire systems, such as braking and steering, are just as stringent as the ones they are replacing. On the other hand, drive-by-wire components should be costwise competitive with conventional technologies. Therefore, there is always limited scope for hardware redundancy, which means that the drive-by-wire systems have to be inherently safe and reliable [1]–[5].

A brake-by-wire (BBW) system design generally comprises electromechanical brake calipers (e-caliper) with embedded brake-torque controllers at each vehicle corner, wheel-speed and vehicle-motion sensors, a central controller unit, and a human–machine interface, such as an instrumented brake pedal, all communicating via a fault-tolerant communications network [5]–[9].

A block diagram of the e-caliper control system is shown in Fig. 1, including the connections between the central control unit (CCU) and one of the four e-calipers in the electromechanical-braking (EMB) system. The CCU is the central vehicle dynamic control unit in the EMB system and generates the brake commands that are required to perform high-level braking tasks, such as antiskid braking (ABS), vehicle-stability control (VSC), or traction control (TC). These commands are sent to the four e-calipers via a communication network. These brake commands are in the form of the desired clamp force to be generated by each e-caliper. Such commands are usually generated in CCU by processing the clamp force and displacement measurements in the calipers and the wheel-speed measurements. A local controller in each caliper regulates the electric current that drives the brake actuator.

A schematic diagram of the e-caliper developed by PBR Australia is shown in Fig. 2. In this design, the rotational displacement of the brake actuator is converted to transitional displacement of a ball-screw through a planetary gear-set. This causes the load sleeve to push the brake pad toward the brake disc and generate the clamp force.

Measurement of the position and speed of the actuator and the resulting clamp force in the caliper are safety-critical tasks in an EMB system, because those measurement are the key variables used by the CCU to generate the brake commands.

The position and speed of the actuators are measured by resolvers (as shown in Fig. 2). A hybrid technique has already been developed to obtain accurate and robust estimates of position and speed of the actuators by processing the resolver signals [7]. Automatic calibration of the resolver parameters (that vary with temperature, pad wear, and aging) has been separately studied, and a new technique has been suggested [8]. Both techniques are efficient in terms of their accuracy, memory usage, and computational complexity and can be implemented in real-time. Thus, we assume that reliable and accurate measurements for the position and speed of the actuators in Figs. 1 and 2 are available.

The CCU and the caliper local controllers require accurate knowledge of the characteristic curve of the calipers, i.e., the profile of the clamp force versus pad displacement. In addition, the accurate characteristic curve of e-calipers can be utilized to calculate clamp-force estimates from the displacements measured by resolvers. Fusion of the direct force measurements given by the sensors with their alternative estimates from...
Rotational displacement of the caliper actuator is transformed to pad movement via the planetary gear-set and ball-screw, and based on the kinematics of this transformation, the actuator and pad displacements are almost proportional. Therefore, without noteworthy loss of accuracy, we study the profile of clamp force measurement against the actuator position.

Characteristic curve varies with aging and environmental conditions (e.g., temperature and humidity) and should be accurately calibrated in real time. Such a calibration can only be performed by utilizing recent samples of the measured forces and their corresponding displacements. Therefore, the accuracy of e-caliper calibration significantly depends on the accuracy of clamp force measurements.

Since the stress in the load sleeve is almost uniformly distributed over the cross section, for the purpose of measurement of the very large loads experienced in a brake caliper, the load sleeve can be considered as an axially loaded spring element.

Thus, load cells are used to measure the clamp force. Fig. 3 shows the arrangement of the strain gauges in each load cell on the load sleeve and their electrical circuitry. In each load cell, adjacent strain gauges are connected in opposite bridge arms to remove bending strains resulting from off-axis or transverse components of forces. Moreover, the strain gauges are oriented transversely to desensitize the bridge output to temperature changes [13].

When the load cell measurements are plotted against the actuator displacement, the result involves hysteresis around the true characteristic curve of the caliper, as shown in Fig. 4. This hysteresis is caused by the presliding component of the friction that exists between the key (placed to prevent the load sleeve from rotating with the ball-screw) and its keyway inside the housing of the load sleeve—see Fig. 5.

To obtain accurate clamp force measurements for caliper calibration and control, the hysteretic friction component of the force measurements provided by the load cells should be detected and removed. The friction modeling and estimation procedure applied by the system should be simple and efficient.
in terms of its required memory and computational power. This is because of the limits of the processing power of CCU (Fig. 1) and the available memory in the system. Such limits are usually imposed for the reduction of mass-production costs. In addition, besides the identification of the hysteresis part and removing it from the measured clamp force (to obtain a reliable measurement) and calibration of the characteristic curve, there are many other complicated processing jobs to be performed by the CCU using its available memory and computational power. Some examples are vehicle-state estimation, ABS, VSC, and TC.

This paper introduces a memory and computationally efficient technique for the identification of the hysteresis part of the measurements, extracting reliable estimates of clamp forces, and real-time calibration of characteristic curve using the estimated clamp forces. In Section II, different hysteresis models are reviewed, and an appropriate model (with the desired accuracy and computational complexity) is selected to be applied for the extraction of the true clamp force from the hysteric measurements. A memory and computationally efficient technique for automatic tuning of the characteristic curve of the caliper is explained in Section III. Experimental results are presented in Section IV, and Section V concludes this paper.

II. HYSTERESIS MODELING

As seen in the example shown in Fig. 4, the clamp force measured by the strain gauges (hereafter, the set of the six load cells are called internal-clamp-force sensor or internal sensor for short) comprises two parts: the real clamp force that causes the axial load on the load sleeve and changes the resistance of the strain gauges and the sliding friction force between the key on the load sleeve and the keyway in its housing. To obtain an accurate measurement of the clamp force, the friction part should be estimated and removed. Since this friction force causes the hysteresis phenomenon, a hysteresis model can be used to estimate the friction force.

Hsu and Ngo [14] have introduced a Hammerstein configuration, which includes a Hammerstein-based dynamic model for hysteresis. This model includes a nonlinear static block followed by a linear dynamic block and is applied to model the rate-dependent and temperature-dependent hysteresis phenomenon. Li and Tan [15] have applied a neural network to estimate the influence of hysteresis for adaptive control of a nonlinear system which involves hysteresis. The above two approaches are too complicated to be implemented in real-time BBW systems.

Oh et al. [16] have analyzed the Dahl et al. friction models as Duhem hysteresis models, classifying each model as either a generalized or a semilinear Duhem model. In this paper, we follow their unified treatment of Duhem-based friction models to investigate the friction-induced hysteresis in e-calipers. Through some experiments (explained in Section IV), we show that by using the Maxwell-slip model to capture the hysteresis part of the load cell measurements, clamp force estimates with sufficient accuracy\(^1\) are obtained.

A. Maxwell-Slip Model

In Maxwell-slip model, the hysteretic slippage is modeled as \(M\) zero-mass elastoslip elements connected in parallel, as shown in Fig. 6. Each element of this model is characterized by its stiffness \(K_i\), position \(x_i(t)\), spring deflection \(\delta_i(t) = x(t) - x_i(t)\), and maximum spring deflection \(\Delta_i\) (before the element \(i\) starts to slip). The input displacement \(x(t)\) is common to all elements. The total hysteretic friction force \(f_f\) is given by the summation of all operators’ spring forces

\[
f_f(t) = \sum_{i=1}^{M} K_i \Delta_i \tilde{\delta}_i(t)
\]

where \(\tilde{\delta}_i(t)\) is given by

\[
\tilde{\delta}_i(t) = \begin{cases} \frac{\delta_i(t)}{\Delta_i}, & \text{if } |\delta_i(t)| < \Delta_i \text{ (stick)} \\ \text{sgn}(\delta_i(t)), & \text{if } |\delta_i(t)| \geq \Delta_i \text{ (slip)} \end{cases}
\]

\(^1\)The minimum accuracy of clamp force measurement—required by high-level braking functions in CCU—is around 99% accurate over the range of clamp force variations 0–40 KN.
and the dynamics of the element position \( x_i(t) \) are as follows:

\[
x_i(t + 1) = \begin{cases} 
  x_i(t), & \text{if } |\delta_i(t)| < \Delta_i \text{ (stick)} \\
  x(t) - \text{sgn}(\delta_i(t)) \Delta_i, & \text{if } |\delta_i(t)| \geq \Delta_i \text{ (slip)}. 
\end{cases}
\]

Fig. 7 shows the friction force \( f_f \) given by the above model plotted versus the displacement \( x \). We observe that the model results in a hysteretic friction force varying within \(-\sum_{i=1}^{M} K_i \Delta_{i0}^0 + \sum_{i=1}^{M} K_i \Delta_{i1}^0\), and the higher the number of elements \( M \), the smoother the curve is. The center of the hysteresis curve along the \( x \)-axis depends on the location of the actuator at the beginning of the hysteresis cycle.

To model the hysteresis in the e-caliper application, we assume that the \( M \) points are evenly distributed over the maximum sticking displacement \( \Delta_{\text{max}} \)

\[
\Delta_i = \frac{i}{M} \Delta_{\text{max}}; \quad i = 1, \ldots, M. ~ (4)
\]

The maximum sticking displacement can be calculated from some previously recorded force-displacement measurements: It is the displacement at which the maximum deflection from the characteristic curve is observed. This deflection is caused by the presliding friction, and for larger displacements, the measured clamp force follows a path that is almost parallel to the characteristic curve.

### III. Characteristic-Curve Calibration: Algorithm

In our previous works [9], [11], we have shown that the characteristic curve of the e-caliper can be modeled by a third-order polynomial. The measurements given by the internal clamp force sensor are modeled as the sum of two parts: the clamping component and the friction component. The clamping component is a third-order polynomial function of the displacement (given by the characteristic-curve model), and the friction component is given by Maxwell-slip model, as described in Section II-A:

\[
\hat{f}_c(t) = Ax(t)^3 + Bx(t)^2 + Cx(t) + D + \sum_{i=1}^{M} K_i \Delta_i \tilde{\delta}_i(t). \quad (5)
\]

The parameters \( \{\Delta_1, \ldots, \Delta_M\} \) are assumed to be known \textit{a priori} by using (4). Characteristic-curve parameters \( A, B, C, \) and \( D \), and the linear coefficients of the hysteresis model \( \{K_1, \ldots, K_M\} \) are determined by fitting an ensemble of data to the earlier model by simply using least squares technique.

An appropriate ensemble of data samples \( \{(x(i), \hat{f}_c(i))\} \) should contain points around a full hysteresis cycle on the force-displacement plot. As the data samples are sequentially received by the CCU through the communication network, the CCU should be able to detect the starting point of a hysteresis cycle so as to start recording data samples until the end of the cycle (before the next starting point). Before a new hysteresis cycle begins, the position coordinate \( x \) is decreasing with time (data points are moving on the lower half of the current hysteresis cycle as shown in Fig. 7), and as soon as a new cycle starts, the \( x \)-coordinate begins to increase with time. Therefore, we suggest that a starting point is detected as follows:

\[
\begin{align*}
  x(i) > x(i - n_0) & \quad \text{or} \quad x(i - n_0) < x(i - 2n_0) \\
\end{align*}
\]

The parameter \( n_0 \) prevents the incorrect detection of a starting point due to the fluctuations of displacement signals (caused by noise). However, there is a tradeoff, as a large \( n_0 \) would result in late detection of the starting point of hysteresis cycles. An appropriate value for \( n_0 \) depends on the application-specific factors, such as sampling rate, signal-to-noise ratio of the position.
measurements, and nominal and maximum actuator speeds, and can be determined by trial and error through experiments.

Because of memory limitations, recording of all data samples in a hysteresis cycle is not feasible. Assume that only $L$ samples of $\{ (x(i), f_c(i)) \}$ pairs out of the data samples in each hysteresis cycle can be recorded in determining the parameters of the model [see (5)]. An iterative method is needed for optimal selection and recording of the data samples as they are consecutively received by the central controller via the communication network. The recorded data samples should be distributed around the hysteresis cycle as evenly as possible. For this purpose, the mutual distances between the recorded samples in the force-displacement plane need to be maximized. We have devised the following iterative method to perform this maximization while choosing the data samples for model fitting.

When a starting point is detected, the next first $L$ data samples $\{(x(i), f_c(i))\}$ are recorded and denoted by $\{x_{temp}(1), \ldots, x_{temp}(L)\}$ and $\{f_{temp}(1), \ldots, f_{temp}(L)\}$. Upon receiving the next data sample by the CCU, that sample is also recorded and denoted by $x_{temp}(L + 1), f_{temp}(L + 1)$. A normalized geometric distance between two consecutive data samples is defined as

$$d_k = \sqrt{\left(\frac{x_{temp}(k+1) - x_{temp}(k)}{X_{max} - X_{min}}\right)^2 + \left(\frac{f_{temp}(k+1) - f_{temp}(k)}{F_{max} - F_{min}}\right)^2}$$

(7)

where $1 \leq k \leq L$ and $F_{max}$ and $F_{min}$ are the upper and lower bounds of clamp-force variations, and $X_{max}$ and $X_{min}$ are similar quantities for displacement, and in practice, they can be determined offline. Let $d_j$ be the smallest distance among the $L$ mutual distances which can be easily recorded and updated iteratively as new samples arrive. If $j = L$, then the new sample (the $(L + 1)$th sample) is too close to its previous sample and is not recorded. If $j < L$, then the normalized geometric distance between the $j$th and $(j + 1)$th samples is the smallest distance. Therefore, the last $L - j$ data samples are left-shifted in the memory, and the new sample is stored as the $L$th location.

First left-shift:

$$f_{temp}(j + 1) \rightarrow f_{temp}(j)$$

$$x_{temp}(j + 1) \rightarrow x_{temp}(j)$$

Second left-shift:

$$f_{temp}(j + 2) \rightarrow f_{temp}(j + 1)$$

$$x_{temp}(j + 2) \rightarrow x_{temp}(j + 1)$$

: \hspace{10cm} \vdots$$

$L$th left-shift:

$$f_{temp}(L + 1) \rightarrow f_{temp}(L)$$

$$x_{temp}(L + 1) \rightarrow x_{temp}(L).$$

The earlier scheme is repeated until the cycle finishes and the starting point of a new cycle is detected.

As shown in Fig. 4, a full cycle may include hysteretic variations around a small part of the whole characteristic curve of the caliper. Therefore, the use of least squares for fitting the model (5) to the data recorded from a single cycle will only locally enhance the characteristic curve. To resolve this issue, considering memory limitations, we select $N + 1$ points ($N$ is assumed to be predetermined based on the available memory space) with their $x$ coordinates evenly distributed over the whole range of variations of displacements $[X_{min}, X_{max}]$, and call them principal fitting points or PF points for short. The displacement coordinates of PF points are calculated using a third-order polynomial model with the last updated values of $A, B, C,$ and $D$ as its parameters. When a local hysteresis cycle finishes and the next one starts, a new set of parameters, for example, $A', B', C'$, and $D'$ are estimated. For each of the PF points whose displacement coordinate is between the minimum and maximum range of the local hysteresis cycle, the force coordinate is replaced with the measure given by the new parameters $A', B', C'$, and $D'$. Then, a third-order polynomial is fitted to the PF points, and the parameters $A, B, C,$ and $D$ are updated. Fig. 8 shows an example of this part of the parameter updating process.

A detailed flowchart of the complete algorithm for real-time calibration of caliper characteristic curve is shown in Fig. 9. There is an Initialization block in which an initial set of model (and other required) parameters of the proposed technique are inputted, the first hysteresis cycle is detected, and the locations of hysteresis elements $\{x_0(1), \ldots, x_0(M)\}$ are initialized. Then, in the Iterative Parameter Updating block, the next hysteresis cycles are detected, and the characteristic-curve parameters are updated iteratively, as next data samples become available to the CCU.

IV. EXPERIMENTAL RESULTS

The performance of the proposed real-time calibration technique was examined through a series of experiments conducted using the e-caliper of the EMB system developed at PBR Australia. The e-caliper was placed in an environmental chamber which provided a controlled temperature and humidity.
Fig. 9. Flowchart for the proposed automatic calibration technique using the hysteresis model (5).

Fig. 10 shows a picture of the experimental setup. The PC is running Vector CANape under Windows XP. It also controls the e-caliper and records the position, temperature, and clamp force measurements provided by caliper sensors. CANape also controls the 42-V power supply (a Delta Elektronika SM70-45D power supply for the e-caliper actuator and BBW circuitry) via a standard National Instruments DAQ break out box connected to a PCI-MIO16E4 PCI card installed in the PC. An external force sensor has been also used to measure and record the true clamp force between the brake pad and brake disc.
In each experiment, the measurements provided by the internal and external force sensors and the position sensor (resolver) were recorded in a specific temperature. In a total number of 14 experiments, the temperature varied between 28°C and 54°C (in 2°C increments). In each experiment, the e-caliper was commanded by CANape to follow a number of consecutive sinusoidal displacements with increasing amplitudes, as shown in Fig. 11. The force-displacement plot shown in Fig. 4 includes the data recordings at 40°C.

To show the variations of characteristic curve with temperature, in Fig. 12, we have plotted the true clamp forces against actuator displacements in three different temperatures. By using the proposed technique to estimate the friction force and correct the hysteretic part of the clamp force measurements provided by the internal sensors, we have estimated the true clamp force from the internal measurements and used them to calibrate the characteristic curve.

Fig. 13 shows the true clamp forces (given by external measurements) and the estimates from the internal measurements, plotted versus time. It is observed that the force estimates obtained from the internal measurements by the proposed technique closely follow the external clamp force measurements. To quantify the accuracy of clamp-force estimates, we have calculated the error of the force estimates with respect to their true values and plotted the error signal versus time, as shown in Fig. 14. It is observed that the clamp-force-measurement error does not exceed 0.27 kN. According to the technical specifications of the EMB design developed at PBR Australia, the high-level braking modules require clamp force measurements with a maximum error of 1% over the range 0–40 kN. This error limit has been devised by EMB design experts through multiple tests of the EMB prototype in various road conditions and braking scenarios. A maximum error of 0.27 kN achieved in our experiments is equivalent to 0.7% error over the range...
0–40 kN, and therefore, the proposed method is applicable for clamp force measurement and caliper calibration in the EMB system.

V. Conclusion

In this paper, a real-time calibration technique for BBW calipers has been introduced. The proposed method is computationally inexpensive and memory-efficient and can be easily implemented into an EMB system. In this method, upon the starting of each hysteresis cycle, a clamp-force model is fitted to the data samples recorded from the previous hysteresis cycle. The clamp-force model includes a Maxwell-slip model for the hysteresis caused by friction. As a result, a set of model parameters estimates for the characteristic curve are obtained. Then, this model is applied to update the characteristic curve over the entire range of force-displacement variations. In a series of experiments, a BBW caliper was controlled to follow a sinusoidal displacement pattern in different temperatures, and the displacement data and force-sensor readings were recorded, along with the true clamp force measured by an external force sensor. The proposed technique was applied to extract the true clamp force from the hysteretic internal force-sensor readings and to update the characteristic curve in real-time. The results show a clamp-force-measurement error of less than 0.7% over the range of 0–40 kN, and using these measurements, the characteristic curve is automatically calibrated in real time with desirable accuracy.

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REFERENCES


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