

A KALMAN FILTERING APPROACH TO ESTIMATE CLAMP FORCE IN BRAKE-BY-WIRE SYSTEMS

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Keywords: Brake-by-wire, sensor fusion, dynamic stiffness, torque balance, optimisation.

Abstract: Removing a clamp force sensor from brake-by-wire (BBW) system designs has been driven by the need to reduce costs and design complexities. In this paper an improved method is presented to estimate clamp force using other sensory information. The proposed estimator is based on the Kalman filter where the actuator resolver is used in a dynamic stiffness model and the actuator current sensors as well as the resolver are used to give measurement updates in a torque balance model. Experimental results show that the estimator can handle highly dynamic braking scenarios making it suitable for possible use in anti-lock braking system (ABS) controls. A comparison is made with a previous attempt to estimate clamp force in BBW systems and it is shown that the proposed estimator improves the root mean square error (RMSE) of estimation. A training strategy is explained to ensure that the estimator can adequately adapt to parameter variations associated with wear. This paper finally discusses reliability issues associated with the developed clamp force estimator.

1 INTRODUCTION

Drive-by-wire (DBW) technologies are being currently developed and introduced into the automotive industry. One advantage of such technologies is to produce intelligent vehicle control systems that improve performance by benefiting from the integration of electronic systems (Schenk et al. 1995). The subject technology of interest in this paper is BBW systems for disk brakes. Figure 1 shows a schematic diagram of a BBW system as given by Saric et. al. (2007). A pedal feel emulator

provides the human-machine interface in a BBW system. This pedal is fitted with sensors whose outputs are processed by an electronic control unit which then controls the actuators.

An electric motor that is coupled to reduction gearing is the general setup used for an electro-mechanical brake (EMB) actuator. The motor is normally of a permanent magnet brushless DC type for the reasons of compactness and enhanced commutation efficiency. A planetary gear-set connected to a ball-screw are generally the components used in the reduction gearing.

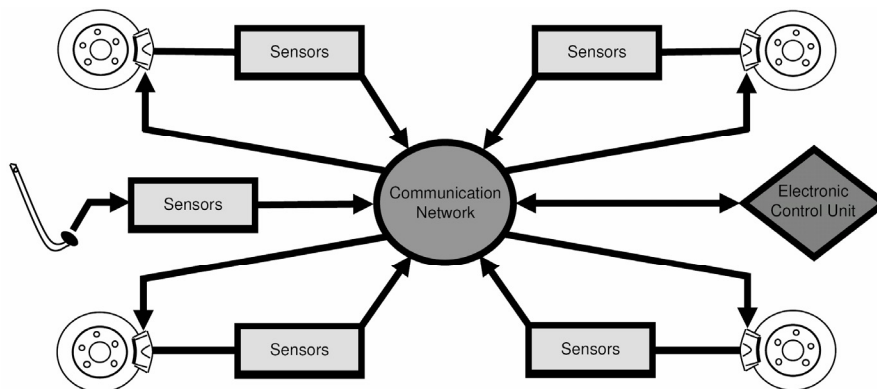


Figure 1: BBW System.

To control EMB caliper clamping force, a clamp force sensor is typically used to close the control loop. A standard motion control architecture (cascaded position, velocity and current control loops) which is slightly altered can be used to control an EMB. Line et al. (2004) exchange the position control loop for a force control loop for EMB control purposes. This architecture is shown in figure 2 as given by Hoseinnezhad et. al. (2006). The control system depicted in figure 2 requires the use of a displacement sensor, normally a resolver, and three motor current sensors for a three phase brushless DC motor.

The adequate implementation of a clamp force sensor in an EMB system can be a difficult thing to achieve. If a clamp force sensor is placed near to a brake pad, it must then be able to mechanically withstand the high temperatures (up to 800 °C) it will be subject to. Also temperature drifts may need to be compensated for. By embedding a clamp force sensor deep within a caliper, i.e. at the near end of the ball-screw this situation can be avoided. However due to the effects of friction between the embedded clamp force sensor location and an inner pad, a hysteresis effect results which prevents a true clamp force to be sensed. A clamp force sensor is a costly item in an EMB caliper. This is due to a high supplier cost and increased production expenses due to its inclusion. These high production costs result from online calibration for each individual sensor because of performance variability from one unit to another, as well as difficult assembly procedures due to the small tolerances being dealt with.

The elimination of a clamp force sensor from EMB designs is highly desirable because of the cost issues and engineering challenges involved with its use. A way to eliminate this component may be realized via a sensor fusion approach, that is, to

estimate clamp force using remaining EMB system sensors.

The introduction given here is followed by a developmental background that briefly explains previous works completed on estimating clamp force in EMB systems. A description of the developmental steps taken to attain our new clamp force estimator is then provided, followed by describing the test rig which we have employed. Validation results are given which then finally leads to conclusive remarks.

2 BBW CLAMP FORCE ESTIMATION REVIEW

Developed torque in an EMB caliper can be determined from motor current sensors which are part of all EMB designs. A simplified model says that the torque induced by a permanent magnet DC motor is linearly related to the current passing through the field coil, that is:

$$T_m = K_m I_m \tag{1}$$

where T_m , I_m and K_m are the motor torque, the field current and the motor torque constant respectively. The latter term is a constant that is experimentally determined. For a brushless permanent magnet DC motor the current (I_m) is the quadrature component of the resultant current space vector as found from the individual phases (Krishnan 2001, p. 527). Since the motor torque input in an EMB caliper causes a clamping force, it is apparent that a relationship must exist between these two variables. To determine an induced clamp force in an EMB caliper using motor current information, a torque balance

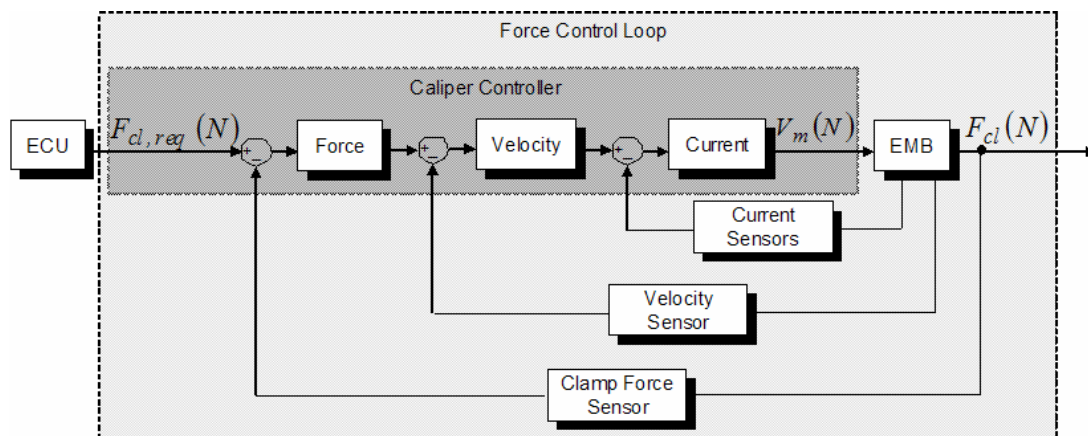


Figure 2: EMB system control architecture.

can be solved as follows:

$$\begin{aligned} T_m &= T_a + T_i + T_f \\ I_m K_m &= \gamma_{tot} F_{cl} + J_{tot} d^2 \theta_m / dt^2 + T_f \\ F_{cl} &= (I_m K_m - J_{tot} d^2 \theta_m / dt^2 - T_f) / \gamma_{tot}. \end{aligned} \quad (2)$$

The torque balance says that the torque developed by the motor (T_m) equals the torque required to provide clamping force (T_a), to meet the necessary inertial demands (T_i) and to overcome frictional resistance (T_f). By combining the load ratios from a series connected planetary gear-set and ball-screw, it can be found that this value (γ_{tot}) acts as a gain relating the application torque (T_a) to the clamp force (F_{cl}). The entire caliper inertia (J_{tot}) is lumped and involves both rotational and translational motions. This value is usually attained using empirical data where an energy balance, over a stage of motor acceleration, is formulated to find the lumped inertia (J_{tot}).

Equation (2) shows that the frictional torque (T_f) term is undefined. The reason for this is that as Olsson et al. (1998, p. 176) explain, using theoretical friction models for practical purposes is difficult to achieve in a satisfactory manner. To overcome this problem, theoretical friction models should be merged with experimentally established phenomena unique to a particular system. Friction models of any sort tend to be avoided in trying to estimate clamp force in an EMB caliper because of the problems in trying to account for wear in the reduction gearing. This subject will be continued in later discussion.

A clamp force estimation algorithm was developed by Schwarz et al. (1999) for use on an EMB caliper designed for a disk brake. Equation (2) was involved in part within their algorithm. By employing a differencing technique they avoid the need for using a friction model which is explained in more detail as follows. A low amplitude high frequency sinusoid is superimposed on the otherwise normal angular motion from the motor. This forces the motor to pass the same angular position in a finite length of time between a clamping and releasing action. At both these instants the application of (2) yields:

$$T_{m,cl} = \gamma_{tot} F_{cl} + J_{tot} d^2 \theta_{m,cl} / dt^2 + T_f \quad (3)$$

$$T_{m,rl} = \gamma_{tot} F_{cl} + J_{tot} d^2 \theta_{m,rl} / dt^2 - T_f \quad (4)$$

where the subscripts *cl* and *rl* indicate clamping and releasing respectively. The friction terms in (3) and (4) have approximately the same magnitudes but opposite signs due to the change in course of motor travel. Adding (3) and (4) cancels out the friction

terms and after some manipulation the following equation to estimate clamp force (F_{cl}^*) can be found:

$$F_{cl}^* = (T_{m,cl} + T_{m,rl} - J_{tot} d(\theta_{m,cl} + \theta_{m,rl}) / dt) / (2\gamma_{tot}). \quad (5)$$

Passing the same motor angle via sinusoidal differing becomes a harder and harder task to achieve as the clamp force application rate is increased. Also the requirement of reversing direction in a short period of time during increased clamp force application rates will most likely challenge the dynamic control ability of the EMB system. A means to cope with these problems is proposed by Schwarz et al. (1999). The characteristic curve of an EMB caliper is a relationship between motor angle and applied clamp force where the former is varied in a pseudo-static fashion. Figure 3 displays this curve for an EMB caliper as given by Hoseinnezhad et al. (2006). Schwarz et al. (1999) put forward the use of a caliper characteristic curve to provide feedback control of applied clamp force. When the opportunity to use (5) arises, it is done so with the intentions of adapting the parameters in the characteristic curve due to pad wear.

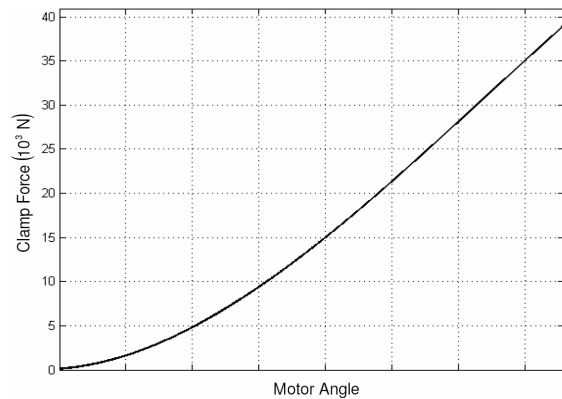


Figure 3: Characteristic curve for an EMB Caliper.

As provided by Hoseinnezhad et al. (2006), figure 4 displays clamp force versus motor angle for a highly dynamic situation where the motor angle is varied in a uniform random fashion with a sample time of 100 ms. It is clear that considerable dynamic exists within the system and that the use of a characteristic curve for clamp force estimation purposes has its limitations for highly dynamic scenarios. The cause of this dynamic is attributed to viscoelastic effects exhibited mainly by the caliper bridge. Hoseinnezhad et al. (2006) developed a dynamic stiffness model to handle such viscoelastic

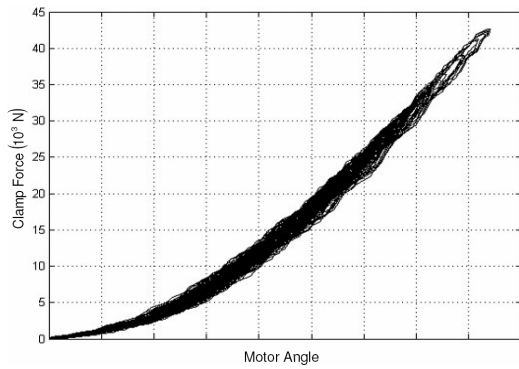


Figure 4: Clamp force versus motor angle for highly dynamic case.

effects. This model is given as follows in discrete time notation:

$$F_{cl}^*(k) = \alpha_3 \theta_m^3(k) + \alpha_2 \theta_m^2(k) + \alpha_1 \theta_m(k) + \alpha_0 F_{cl}^*(k-1) \quad (6)$$

where α_4 , α_3 , α_2 , α_1 and α_0 are experimentally determined constants and θ_m is the motor angle.

Saric et al. (2006, 2007) uses (6) as well as a second model to estimate clamp force in a fusion algorithm which optimizes the RMSE of estimation. The second model is based on the torque balance approach where a dynamic Coulomb friction model is used which is dependent on clamp force and is shown below in discrete time notations:

$$F_{cl}^*(k) = \frac{T_m(k) - \frac{J_{rot}}{t_s^2} (\theta_m(k) - 2\theta_m(k-1) + \theta_m(k-2)) - A_k \operatorname{sgn}(\theta_m(k) - \theta_m(k-1))}{\gamma_{tot} + \mu_k \operatorname{sgn}(\theta_m(k) - \theta_m(k-1))} \quad (7)$$

where t_s , μ and A are the sampling time, the coefficient of Coulomb friction and an offset friction term respectively. The two models given by (6) and (7) are fused together by Saric et al. (2006, 2007) using a maximum likelihood estimator to give an optimized estimate of clamp force which is as follows:

$$\hat{F}_{cl}(k) = F_{ds}^*(k) + \frac{\sigma_{ds}^2}{\sigma_{ds}^2 + \sigma_{tb}^2} (F_{tb}^*(k) - F_{ds}^*(k)) \quad (8)$$

where σ is the standard deviation and the subscripts ds and tb indicate dynamic stiffness and torque balance respectively. Gaussian noises were assumed in the derivation of (8). After having adapted parameters, as detailed by Saric et. al. (2007) and described previously, an improvement in the RMSE of approximately 10% is obtained as a result of

fusing via (8). Parameters are adapted in (6) due to stiffness variations because of pad wear, and in (7) because of frictional variations in the caliper reduction gearing.

The fusion algorithm used by Saric et al. (2006, 2007) does not have a recursive nature. Therefore the use of a Kalman filter will further improve estimation accuracy (Kalman 1960, p. 35; Sorenson 1970, p. 63). In this paper we present the use of a Kalman filter to estimate clamp force. The ensuing section details how we setup the Kalman filter for clamp force estimation purposes in a BBW system.

3 KALMAN FILTER SETUP

A Kalman filter is a linear, recursive, discrete time estimation algorithm. It is maximum likelihood in nature in that the RMSE's are minimized. A Kalman filter is implemented widely in control systems to give improved system state estimates. Figure 5 shows a block diagram representation of a Kalman filter in a control system. The use of a Kalman filter is advantageous because of noise influences (Gaussian) which render the true system states unknown. A Kalman filter uses system dynamics as well as other measurement sources to estimate states. Typically the later is attained from direct sensory measurements. The noises which affect both kinds of estimates the Kalman filter receives, view figure 5, are required to be uncorrelated.

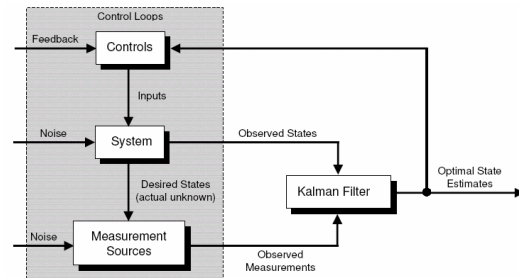


Figure 5: Typical Kalman filter application.

In the case where the system dynamics and/or measurement dynamics (which acts on the system dynamic estimates) is non-linear, an Extended Kalman filter (EKF) can be used which performs a linearization procedure. This is not necessary for our purposes due to the linear nature of the circumstances. Figure 6 shows a block diagram representation of a Kalman filter where:

x - is the system state vector

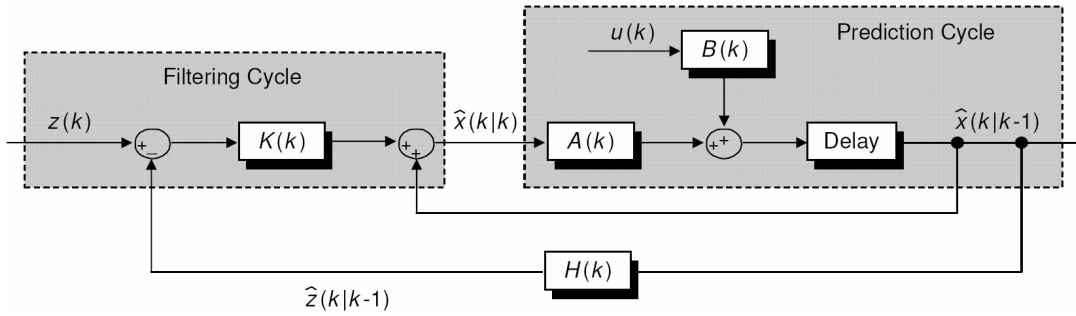


Figure 6: Block diagram representation of a Kalman filter.

- u - is the control inputs
- z - is the observation vector
- K - is the filter gain
- A - is the coefficient matrix of the system
- B - is the driving matrix
- H - is the measurement matrix.

The hat (^) scripts in figure 6 denote the criteria of trying to minimize the RMSE of estimation. The discrete time notation used in figure 6, $k|k-1$, indicates that the estimate at k was determined given knowledge at $k-1$. The filter gain is defined as follows:

$$K(k) = P(k|k-1)H^T(k)(H(k)P(k|k-1)H^T(k) + R)^{-1} \quad (9)$$

where,

- P - is the covariance matrix of state estimates
- R - is the measurement noise covariance matrix.

The matrices $(P(k|k-1))$ and $(P(k|k))$ for a Kalman filter are given below as:

$$P(k|k-1) = A(k)P(k-1|k-1)A(k)^T + Q \quad (10)$$

$$P(k|k) = (I - K(k)H(k))P(k|k-1) \quad (11)$$

where,

- Q - is the system noise covariance matrix
- I - is the identity matrix.

It should be noted that the system noise covariance (Q) and measurement noise covariance (R) matrices may be time-variant, however we assume them here to be constant. As shown in figure 6, a Kalman filter of any type involves the recursive application of

prediction and filtering cycles. Brown and Hwang (1992) give a complete derivation of the Kalman filter algorithm.

To employ a Kalman filter for clamp force estimation in a BBW system, we firstly use (6) as our state space system equation. The constant α_0 from (6) is taken to be equal to $A(k)$ from figure 6. Note that typical matrix notations were not required due to the unit state space dimension of (6). The clamp force in (6) is non-linearly proportional to the motor angle input. This non-linearity does not require the use of an EKF because it is not state dependent. To integrate this non-linearity within the Kalman filtering algorithm given in figure 6 we apply the following equality:

$$B(k)u(k) = \alpha_3\theta_m^3(k) + \alpha_2\theta_m^2(k) + \alpha_1\theta_m(k) \quad (12)$$

We take the equivalent of $\hat{x}(k|k-1)$ from figure 6 to be directly equal to $\hat{z}(k|k-1)$, that is:

$$\hat{z}(k|k-1) = \hat{F}_{cl}(k|k-1). \quad (13)$$

For this situation $H(k)$ is taken to have a constant unit value. We use (7) as our source for measurement updates which is equivalent to $z(k)$ from figure 6. Saric et al. (2007) found that the RMSE's associated with (6) and (7), after having adapted parameters, were 0.35 and 0.61 kN respectively. These values squared are used for assumed constant system (Q) and measurement (R) error variances (the typical term covariance has not been used since (6) has a unit state space dimension).

With the Kalman concept to estimate clamp force in BBW systems defined, the next section briefly describes the test rig required to obtain necessary data for analysis and subsequent validation purposes.

4 EXPERIMENTAL ENVIRONMENT

A test rig was setup for use on a prototype EMB caliper. An external servo motor was used to provide actuation by coupling it to the caliper internal reduction gearing as shown in figure 7. The external motor is of the permanent magnet brushless type, with ratings of 55.5 N.m and 5, 000 rpm and ensures that maximum clamp forces can be achieved. To interface with this motor, the RS232 protocol was utilized. MATLAB's Simulink package along with the xPC block-set provided a real time operating system that was implemented to control the external

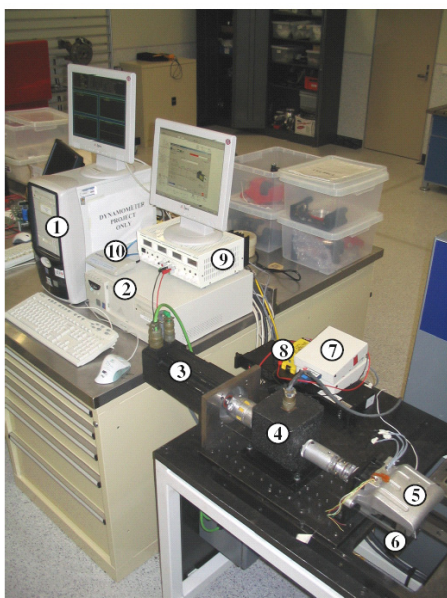


Figure 7: Test rig using a brushless permanent magnet external servo motor.

1. *host PC*
2. *target PC*
3. *brushless permanent magnet external servo motor*
4. *external torque sensor*
5. *EMB caliper*
6. *external clamp force sensor*
7. *National Instruments brake-out boxes*
8. *low pass filter/amplifier for external clamp force sensor*
9. *DC power supply*
10. *ethernet hub*

motor angle. The external motor is controlled by PID controllers within a standard motion control architecture; cascaded position, velocity and current

control loops as illustrated in figure 8. Sensory information are logged by uploading the signal data to the host PC from the target PC, marked 1 and 2 respectively in figure 7. The logged data is stamped at 100 μ s time-step intervals. Both the host and target PC's have Pentium 4 processors operating at 2.4 GHz. To measure the caliper motor angle, an encoder output is taken from the 1:1 coupled external servo motor. The resolution of this encoder output provides 8, 192 counts per revolution. An external torque sensor is used to sense torque input to the EMB caliper. An external clamp force sensor is used to measure the true load induced by the brake pads.

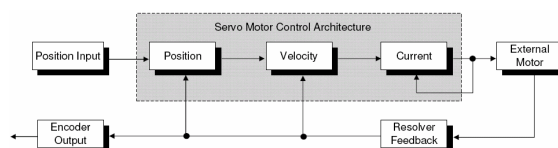


Figure 8: Control scheme used for external servo motor.

For the reasons of clarity the external motor angle and torque data from this test rig is considered to be received from an EMB caliper itself since a resolver and current sensors are available.

5 RESULTS AND DISCUSSIONS

After having adapted parameters in (6) and (7) as detailed by Saric et. al. (2007) and described previously, the Kalman filter setup given earlier for clamp force estimation purposes in a BBW system are applied to uniform random data. The uniform random data involves varying the motor angle in a uniform random manner with a sample time of 100 ms. We use the constant system (Q) error variance to initialize the clamp force estimate error variance at time equal to zero.

Figure 9 shows the performance of our new method to estimate clamp force in a BBW system. This result shows that adaptation to ABS controls is possible seeing as the actuation speeds are comparable. A new RMSE of 0.29 kN results which is an approximately 20 % improvement on the RMSE from the dynamic stiffness model alone. Saric et al. (2007) found that the use of a maximum likelihood estimator with no recursive aspect, as given by (8), gave a RMSE in clamp force estimation of 0.32 kN where the same experimental setup and control input was used as here. Therefore we have demonstrated that the use of an Kalman filter which has a recursive aspect, improves the

RMSE of clamp force estimation by approximately 10 % with regards to the methods used by Saric et. al. (2007).

With in-service pad temperatures being able to possibly reach 800 °C, it has been found that the stiffness of pads varies depending on the temperature (Schwarz et. al. 1998). Stiffness is a large component within the clamp force estimator developed within this paper. The brake pad temperature was kept constant using the static test rig shown in figure 8, and hence temperature effects on clamp force estimation under practical circumstances should be investigated.

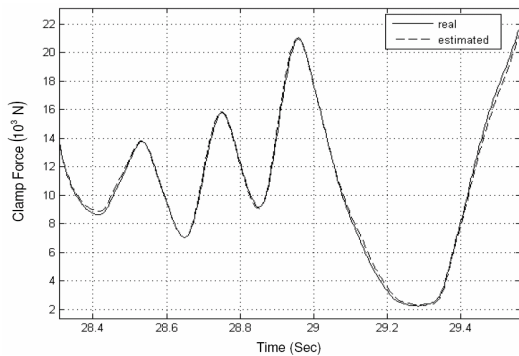


Figure 9: Uniform random data, 100 ms sample time, EKF clamp force estimator validation.

6 CONCLUSIONS

This paper presents the use of a cost effective and design friendly solution for an automotive BBW actuator. The objective of making a clamp force sensor a redundant component in an EMB system is strongly encouraged by the results within this paper. A dynamic stiffness model was used to estimate clamp force which relied on the output from an internal resolver. Based on a torque balance approach, a second model was used to estimate clamp force which relied on the use of internal motor current sensors and an internal resolver. Wear dependent parameters from both models were adapted using an in-service method. The outputs from the two independent models were fused using a Kalman filter to give optimized estimates of clamp force. The developed estimator has been shown via experimental verification to be able to handle highly dynamic braking situations. Also it has been shown that the RMSE of estimation with regards to previous attempts to estimate clamp force in BBW systems has been improved upon. With continued development the possible cost savings inherent with

attempting to make a clamp force sensor redundant can be accomplished in future EMB designs.

ACKNOWLEDGEMENTS

The initiative formed by the centre of Research for Advance By-Wire Technologies (RABiT) provided a medium for which this collaborative work was undertaken by Swinburne University of Technology (SUT) and PGT. The authors of this paper would like to thank the engineers from PGT for their kind assistance.

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