

Multi-Objective Optimization and Robust Design of Brake By Wire System Components

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ABSTRACT

A Brake By Wire (BBW) system is generally composed of electro-mechanical calipers at each wheel, a pedal simulator and a central controller. The brake demand is processed by the pedal and the central controller commands the brake distribution for each brake actuator. The highly responsive and independent brake actuators lead to enhanced controllability which should result in not only better basic braking performance, but also improvements in various active braking functions such as integrated chassis control, driver assistance systems, or cooperative regenerative braking.

Although the BBW system has the potential for numerous advantages and innovations in braking, it has yet to be successfully introduced in series production mainly due to safety and cost concerns. Recent studies have been made to investigate the functional safety aspects and additional mechanical backup measures in this regard. Another area that needs to be considered is the optimization of key BBW system components to increase product competitiveness and cost effectiveness.

In this study, optimization and robust design was carried out for the Electric Wedge Brake (EWB) caliper and the pedal simulator. First, the EWB actuator has a very uncommon wedge mechanism that needs to be designed in the caliper housing. This can lead to various designs of the caliper that can easily grow in size and weight. An optimal design is needed in order for the caliper to have a package competitive size while at the same time maintaining required stiffness. Second, the pedal simulator is the direct connection to the driver that provides the actual braking pedal feel. Thus it is imperative that the pedal simulator is designed to give driver friendly pedal feel without sacrificing its structural integrity.

The multi-objective robust design concept based on the Non-dominated Sorting Genetic Algorithm-ii (NSGA-ii) was used as the optimization method in this investigation. This method considers multiple objective functions and external noise factors, and uses self-learning weight factors. The objective functions for the EWB caliper and pedal simulator were designated as caliper weight and stiffness, and pedal feel and rubber stiffness, respectively. And variations in operation direction were considered as the noise factors for both designs. Finally, Finite Element Analysis (FEA) based on the Design of Experiments (DOE) procedure was used to obtain data to define the objective functions and the resulting robust optimal designs were verified using FEA analyses and experiments.

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INTRODUCTION

The Brake By Wire (BBW) system is generally composed of front and rear Electro-Mechanical Brakes (EMB) which generate wheel clamping forces and a pedal simulator that processes the driver's braking intention. The most common BBW configuration uses four EMBs at each wheel, but as high braking forces on the front axle lead to high power consumption, an alternative has been to use Electric Wedge Brakes (EWB) or other types of self-energizing brakes, which make use of the vehicle kinetic energy for braking [1]. The

EWB has the benefit of using the frictional force between the disc and friction pad which allows for less use of electrical power input while the EMB relies solely on the power input to create the needed clamping force. However, an EWB actuator usually requires a more complex design for functions such as wear adjustment or electric parking and as such using a conventional EMB on the rear has benefits. During normal operation, the brake demand is processed by the pedal and the main controller will command the amount of braking required by the actuators of each wheel. The pedal simulator has stroke and force sensors to recognize the driver's desired

brake demand and the front EWB and rear EMB are composed of the caliper, torque member, actuator housing (gear box, screw, wedge mechanism, etc.) and the motor.

In general, BBW systems with highly-responsive and active independent control of the brake actuators at each wheel can lead to great dynamic control flexibility and improved brake performance. Furthermore, integration with other chassis control systems, cooperative regenerative braking, and various driver assistance functions is simple due to such inherent properties. However, BBW systems have yet to be successfully introduced in series production mainly due to the underlying perception of the lack of reliability of electronic components and overall cost concerns. Recent studies have been made to investigate the functional safety aspects [2] and additional mechanical backup measures [3] in this regard. Another area that needs to be considered is the optimization of key BBW system components to increase product competitiveness and cost effectiveness.

In this study, optimization and robust design was carried out for the Electric Wedge Brake (EWB) caliper and the pedal simulator. First, the EWB actuator has a very uncommon wedge mechanism that needs to be designed in the caliper housing. This can lead to various designs of the caliper that can easily grow in size and weight. An optimal design is needed in order for the caliper to have a package competitive size while at the same time maintaining required stiffness. Second, the pedal simulator is the direct connection to the driver that provides the actual braking pedal feel. Thus it is imperative that the pedal simulator is designed to give driver friendly pedal feel without sacrificing its structural integrity.

The multi-objective robust design concept based on the Non-dominated Sorting Genetic Algorithm-ii (NSGA-II) was used as the optimization method in this investigation [4]. This method considers multiple objective functions and external noise factors, and uses self-learning weight factors. The objective functions for the EWB caliper and pedal simulator were designated as caliper weight and stiffness, and pedal feel and rubber stiffness, respectively. And variations in operation direction were considered as the noise factors for both designs. Finite Element Analyses (FEA) are performed based on the Design of Experiments (DOE) procedure to obtain initial values for the optimization and S/N ratios are employed to describe the sensitivities of the objective functions. Finally, the polynomial based Response Surface Method (RSM) takes the initial values as an approximation function for the NSGA-II optimization process and a Pareto solution set is obtained, which shows a robust optimal solution [5].

OPTIMIZATION METHOD

Response Surface Model (RSM)

In general, the regression method is applied to FEA results to build mathematical models to carry out the response surface method [6]. The polynomial function, $f(x)$, for the

regression process is typically chosen as a 2nd order polynomial in order to accommodate the nonlinearity in models as follows:

$$f(x) = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_i \sum_{j>i} \beta_{ij} x_i x_j \quad (1)$$

where, k is the number of design variables. The parameters of β_{ij} are determined via the least square method which minimizes the squared sum of the deviations of the predicted values, $f(x)$, from the actual values, $y(x)$. Such parameters can be obtained using the following relation:

$$\tilde{\beta} = [\bar{X}^T \bar{X}]^{-1} \bar{X}^T \tilde{y} \quad (2)$$

where, $\bar{X}$ is the design matrix calculated from training data, and $\tilde{y}$ is a column vector containing the values of the response of each training data.

Multi-Objective Genetic Algorithm

The solution to a multi-objective problem is a set of design variable values, such that none of the objective functions can be further increased without a decrease in some of the remaining objective functions, i.e. every such value of a design variable is referred to as 'Pareto-optimal'. Pareto-optimal solutions have also been termed non-dominated. This name arises from the fact that no other solution is superior to them in all objectives. In other words, the non-dominated solutions are those solutions that cannot be simultaneously improved in all objectives.

NSGA-II, which is an improved version of NSGA is a multi-objective optimization algorithm that can be used to build an automatic calibration routine. NSGA-II is one of the contemporary multi-objective evolutionary algorithms that exhibits high performance and has been widely applied in various disciplines. The algorithm makes use of a fast non-dominating sorting approach to discriminate solutions, which is based on the concept of Pareto dominance and optimality [7]. According to the definition and notation presented in these previous investigations, the concept of Pareto dominance and optimality can be expressed as follows for a multi-objective minimization problem:

$$\text{Minimize } f(x) = (f_1(x), f_2(x), \dots, f_n(x))$$

$$\text{Subject to } g(x) = (g_1(x), g_2(x), \dots, g_n(x)) \leq 0,$$

(3)

where, $f(x)$ is the vector-valued function, x is the decision vector, $g(x)$ is a vector of constraints, and n is the number of functions. Considering two decision vectors a and b , a is said to dominate b :

$$\begin{aligned} &\text{iff } \forall i \in \{1, 2, \dots, n\} : f_i^j(a) \leq f_i^j(b) \text{ and} \\ &\exists i \in \{1, 2, \dots, n\} : f_i^j(a) < f_i^j(b), \end{aligned} \quad (4)$$

where, j indicates the generation number of the genetic optimization process. It should be noted that a set of decision vectors that are Pareto optimal within the search space together form a Pareto optimal front.

Since NSGA-II is a population-based algorithm, it starts with random generation of a parent population, P_0 , of potential solutions. The parent population, having size n , is checked for Pareto dominance and a fitness value is used to rank the solutions and assign them to the different fronts (i.e., each solution belongs to different fronts based on its domination level). The first front contains solutions that dominate solutions of all other fronts. An offspring population, Q_0 , of the same size as the parent population is created through recombination based on binary tournament selection and by inducing variations using mutation operators. After the initial generation, the procedure involves comparing the current population with previously identified non-dominated solutions (i.e., elitism). The entire procedure for the j -th generation of the first front is described as follows:

1. Combine parent ($P_j = P_0$) and offspring ($Q_j = Q_0$) populations to create R_j of size $2n$, where R_j is the j -th random set.
2. Perform non-dominated sorting on R_j to identify the different fronts F_i , where $i = 1, 2, \dots, n$ and stop here if convergence criteria have been met.
3. Create P_{j+1} of size n by selecting solutions from subsequent non-dominated fronts ($F_1, F_2, \dots, F_n$).
4. Create Q_{j+1} of size n using binary tournament selection based on crowding-comparison operator, crossover and mutation performed on P_{j+1}
5. Repeat steps 1 through 4 until convergence criteria have been met.

ROBUST OPTIMIZATION DESIGN OF THE EWB CALIPER

System Description

The EWB system is based on a self-reinforcing mechanism as shown in Figure 1. For electric brake actuators such as EMB, the clamping force is typically generated by coupling a motor through a gearbox onto a ball- or roller-screw. The actuator output bearings must support the worst case clamping load. By definition, for the motor to produce a torque, electric current is required, resulting in a constant power drain. In practice, a compromise has to be found

between the high gear ratio needed to minimize the current for continuous braking and the low gear ratio which minimizes the current for dynamics [8]. It would clearly be of benefit if the force required from the brake actuator can be reduced, since this would make this compromise much easier to reach. The EWB solves the aforementioned issues efficiently by using a wedge, which exploits self-reinforcement of the braking forces by the rotating brake disk. However the caliper of EWB system has a structural requirement that the actuation parts need to be located inside the caliper. Thus, the size and weight of the EWB caliper becomes larger than hydraulic brakes.

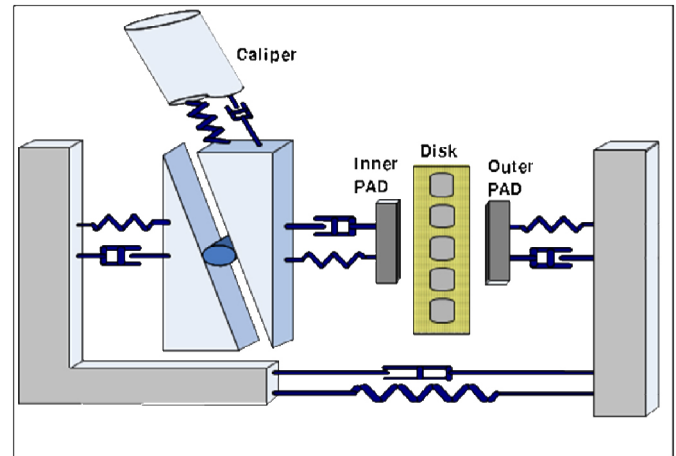


Figure 1. The EWB mechanism model.

Design Formulation

In order to improve EWB performance, the objective functions of weight and stiffness are defined. The stiffness generally means the applied force divided by displacement. In case of a hydraulic caliper, displacement is only considered in one direction because the force only applies in the vertical direction to the caliper body. However, the wedge caliper needs to be considered with a 3-dimensional displacement because of the nature of the applied force direction. Thus, the displacement used to calculate stiffness is defined as in Eqn. (5) and the stiffness is obtained by using this calculated displacement and the applied load.

$$\delta_{ewb_caliper} = \sqrt{\delta_x^2 + \delta_y^2 + \delta_z^2} \quad (5)$$

where, δ_x , δ_y , and δ_z represent the maximum displacement in the x, y and z directions, respectively. To consider not only the mean but also the variability of the objective function in terms of stiffness, a signal-to-noise (S/N) ratio is used as defined in Eqn. (6). The S/N ratio can be considered the sensitivity of the objective function to outside noise factors and a larger values means that the design is more robust against the considered outside influences. For the current case, a larger-the-better (LTB) S/N ratio is adapted to represent maximizing the mean of stiffness, as well as

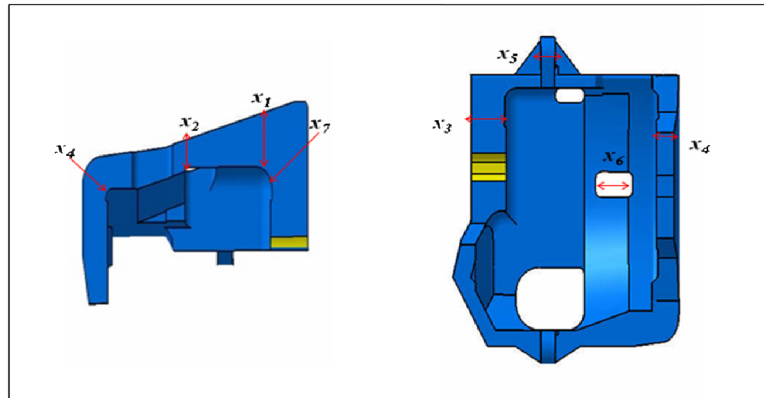


Figure 2. Design variables of the EWB caliper.

minimizing the variability of stiffness with respect to the force direction.

$$S / N_{LTB} = -10 \log \left\{ \frac{(y_1^{-2} + y_2^{-2} + \dots + y_n^{-2})}{n} \right\} \quad (6)$$

where, n is the number of stiffness measurements. A total of eight design variables were chosen based on the how the caliper can be readily modified; thicknesses of the caliper in several regions, interior fillet radii and the upper hole size as shown in Figure 2.

Based on this, the mathematical formulation of the EWB caliper optimization can be stated as follows:

$$\text{Minimize } f_1(x) = y_{\text{weight}} \quad (7-1)$$

$$\text{Maximize } f_2(x) = y_{\text{stiffness}} \quad (7-2)$$

To increase robustness of the design, noise factors can be selected and considered in the optimization process to minimize the output variability. In the present study of the current EWB caliper case, the actuation force direction of the wedge mechanism was taken as the noise factor. The forces were set as angle of $+\alpha$ and $-\alpha$ degrees to the perpendicular force direction as shown in Figure 3. Thus the nominal angle was set as zero degrees (angle = 0 degrees) and the robust design employed three levels of angle, namely, -15 , 0 , and $+15$ degrees.

The noise factor of the wedge actuating direction is considered in the objective function of stiffness as follows:

$$\text{Stiffness} = y_{\text{stiffness}}^0 \quad (8-1)$$

$$S / N_{\text{stiffness}} = -\log \left\{ \frac{((y_{\text{stiffness}}^{-15})^{-2} + (y_{\text{stiffness}}^0)^{-2} + (y_{\text{stiffness}}^{+15})^{-2})}{3} \right\} \quad (8-2)$$

Here, the deterministic Pareto solutions are obtained using the objective functions described in Eqns. (7-1) and (8-1), while the robust Pareto solutions are obtained using the objective functions described in Eqns. (7-1) and (8-2). Both the deterministic and robust solutions are found according to Eqn. (3), Eqn. (4), and the process described in the MULTI-OBJECTIVE GENETIC ALGORITHM section above.

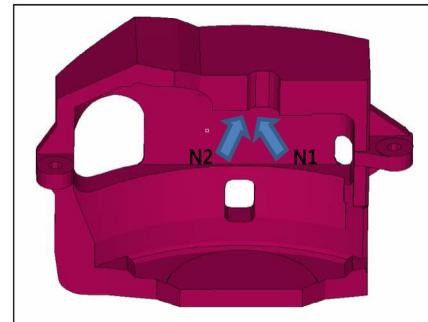


Figure 3. Noise factor considered for the EWB caliper in the current study.

Results and Discussion

For optimization of the EWB caliper, models representing its weight and stiffness were developed using RSM. A mixed orthogonal array of L18 was used to perform DOE because there are design variables with two different levels and interactions can be ignored. Using this experimental design, the levels of each design variables were assumed to be $2^1 \times 3^7$ level, which means one variable had two equally spaced levels of values and seven variables had three levels of equally spaced values.

The FEA was performed by Hyper Mesh for mesh generation and RADIOSS for structure analysis. The FEA results of deflection and stress distribution are shown in Figure 4 and the FEA results of mean values and S/N ratios are given in Table 1.