CASE 60

Reduction of Boosting Force Variation of Brake Boosters

Abstract: A brake booster is a component of an automotive brake system whose function is to boost the pedal force of a driver. The hydraulic force of each cylinder in the brake system is proportional to the foot force. However, the defect rate has not always been satisfactory, due to relatively large boost force variations. To resolve this chronic problem, the robust design method was utilized to improve the design and manufacturing processes. In the robust design experiment, five control factors and two noise factors were allocated in an L_{12} orthogonal array and the dynamic signal-to-noise (SN) ratios were calculated. Through use of the robust design method, we improved the rolled throughput yield dramatically, and the optimum conditions found will be adopted in the design and manufacturing processes.

1. Introduction

The brake booster for the automotive brake system under study, located between the brake pedal and master cylinder, boosts a driver's pedal force to generate enough braking force to stop a vehicle (Figure 1). It uses the vacuum pump system (the intake manifold or built-in vacuum pump) of the engine to boost the pedal force, and that's why it is called *vacuum servo* or *master vac*. To check the brake booster quality, booster forces at two given input forces were inspected to see whether or not they met the target values (Figures 2 and 3). However, unacceptably large variations were found in the booster forces. Therefore, it was decided to use robust design to solve this chronic problem.

2. Background and Objectives

The brake booster forces are generated through three different phases (Figure 3). In the first phase, no force is generated and the input stroke in this phase is regarded as "lost travel." As the input force rises into the second phase, a sudden stepwise booster force, a *jump-in force,* is generated. After the jump-in, the booster force is increased linearly as the input force increases up to the knee point, where the booster force increase rate is suddenly reduced. In the last phase, the booster force increase continues at a reduced rate. *Boost ratios,* ratios of output forces to input forces, jump-in force, and knee point are the major design criteria of the brake booster.

The objective of this study was to reduce the high defect rate of the brake booster by reducing the booster force variations in the second phase, which had been a major chronic problem. To reduce the defect rate, we decided to use the robust design technique to improve the design as well as the manufacturing processes. Since booster manufacturing began about 20 some years ago, various approaches had been adopted earlier to solve this problem. However, no significant improvement had been made until the robust design technique was utilized.

 Taguchi's Quality Engineering Handbook. Genichi Taguchi, Subir Chowdhury and Yuin Wu

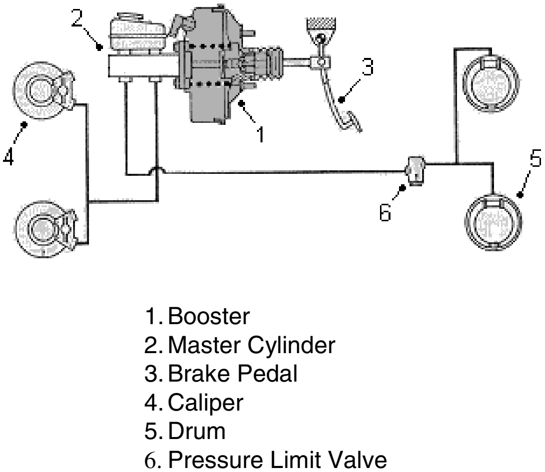

Figure 1
Automotive brake system

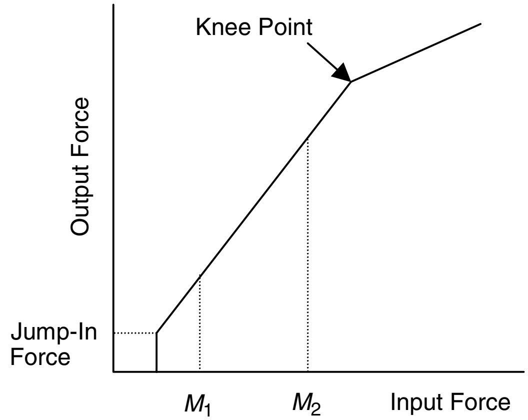

Figure 3
Output characteristics

3. Robust Design Formulation

Several design and manufacturing parameters were considered and a few noise factors were studied, and finally, five control factors and three noise factors were selected, as shown in the P-diagram (Figure 4).

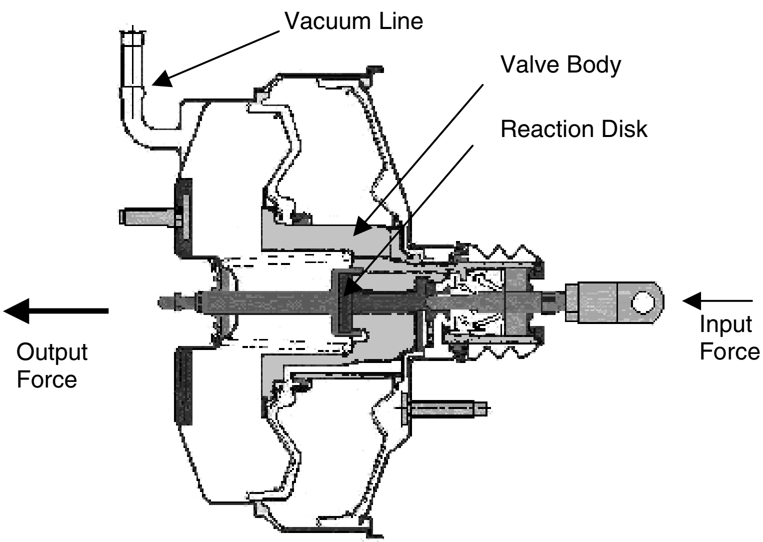

Figure 2
Brake booster

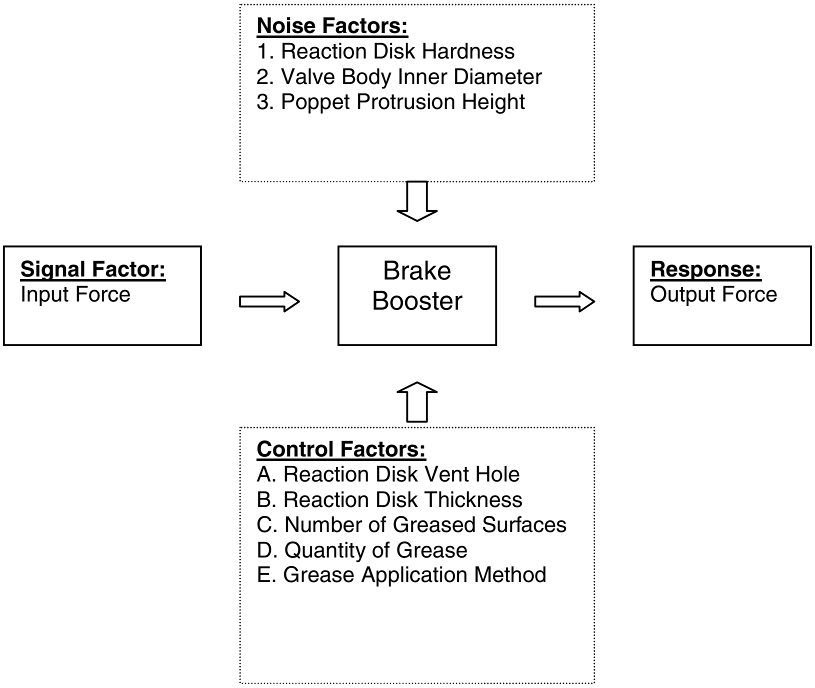

Figure 4
P-diagram

Control Factors and Noise Strategy

Based on the results of several preliminary experiments, a few design parameters were found to contribute to the output force variations as well as several manufacturing processes. Therefore, two design parameters and three manufacturing parameters were selected as control factors (Table 1). Noise factors chosen were primarily geometrical and material variations of parts from suppliers. Three noise factors were combined to represent the best (N_1) and the worst (N_2) noise conditions (Table 2).

Table 1
Control factors

		Level	
	Control Factor	**1**	**2**
A:	reaction disk vent hole	Yes	No
B:	reaction disk thickness	Current	Thicker
C:	number of greased surface	One side	Both sides
D:	quantity of grease	Current	More
E:	grease application method	Current	Better

Table 2
Noise factors

Noise Factor	N_1	N_2
1. Reaction disk hardness	Soft	Hard
2. Valve body inner diameter	Large	Small
3. Poppet protrusion height	Small	Large

Table 3
L_{12} orthogonal array

	Control Factor											M_1		M_2	
No.	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*K*	N_1	N_2	N_1	N_2
1	1	1	1	1	1	1	1	1	1	1	1				
2	1	1	1	1	1	2	2	2	2	2	2				
3	1	1	2	2	2	1	1	1	2	2	2				
4	1	2	1	2	2	1	2	2	1	1	2				
5	1	2	2	1	2	2	1	2	1	2	1				
6	1	2	2	2	1	2	2	1	2	1	1				
7	2	1	2	2	1	1	2	2	1	2	1				
8	2	1	2	1	2	2	2	1	1	1	2				
9	2	1	1	2	2	2	1	2	2	1	1				
10	2	2	2	1	1	1	1	2	2	1	2				
11	2	2	1	2	1	2	1	1	1	2	2				
12	2	2	1	1	2	1	2	1	2	2	1				

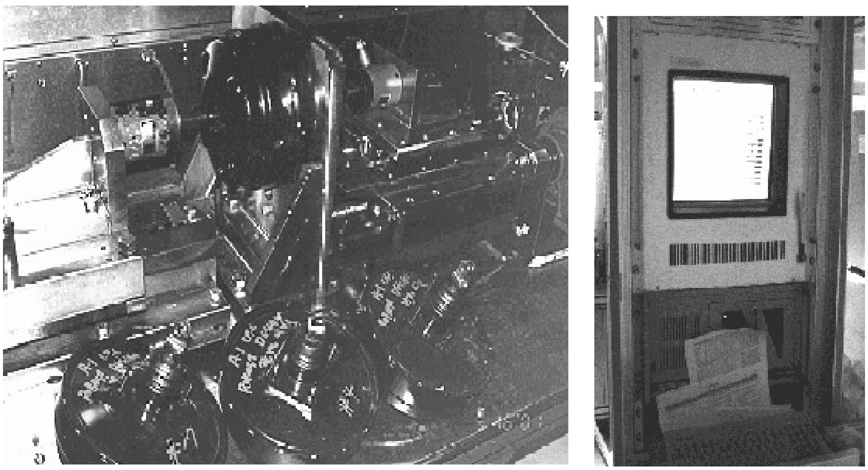

Figure 5
Booster performance tester

Table 4
SN ratio response

	A	*B*	*C*	*D*	*E*
1	−2.11	−1.31	−2.55	−0.65	−1.32
2	0.40	−0.41	0.84	−1.06	−0.39
Δ	2.51216	0.89757	3.38785	0.40884	0.92659
Rank	2	4	1	5	3

Table 5
β response

	A	*B*	*C*	*D*	*E*
1	7.86959	7.80028	7.92845	7.85619	7.8032
2	7.76598	7.83529	7.70712	7.77938	7.83237
Δ	0.10361	0.03501	0.22132	0.07681	0.02917
Rank	2	4	1	3	5

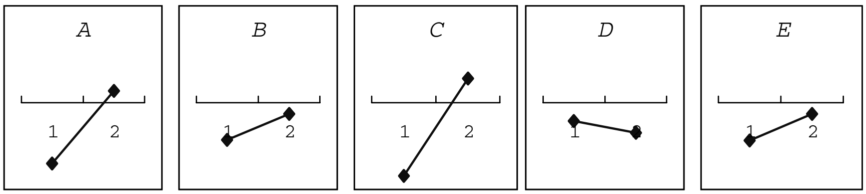

Figure 6
SN ratio response

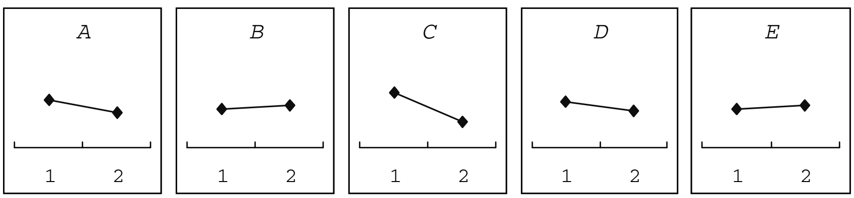

Figure 7
β response

Table 6
SN ratio predicted for a derived optimal condition

Condition	SN Predicted (dB)	Control Factors
Current	−2.00	$A_2B_1C_1D_1E_1$
Optimal	2.31	$A_2B_1C_2D_1E_2$
Gain	4.31	

Orthogonal Array

Since five control factors were identified, the L_{12} orthogonal array was selected for experiments. These control and noise factors were allocated, as shown in the Table 3.

Ideal Function

The following ideal function was used for this study, which can easily be derived from Figure 3:

$$y = \beta M \tag{1}$$

where y is the output force and M is the input force.

Test Equipment

A booster performance tester was used to measure input and output forces of the booster (Figure 5). It supplies vacuum to the booster just like the vacuum pump system of the engine of a vehicle. Its measurement system both records input/output forces and calculates some performance parameters, such as jump-in force, boost ratio, lost travel, and so on.

4. Results and Analysis

The signal-to-noise (SN) ratios (η) and sensitivities (β) were calculated using the following equations:

$$\eta = 10 \log \frac{(1/rr_0)(S_\beta - V_e)}{rV_e} \tag{2}$$

$$\beta = \sqrt{\frac{1}{rr_0}(S_\beta - V_e)} \tag{3}$$

where r is the sum of squares of the signals, r_0 the number of linear equations, S_β the variation caused by β, and V_e the error variance.

The response tables (Tables 4 and 5) and response graphs (Figures 6 and 7) summarize our results. The results show that control factors A, C, and E had large effects on the SN ratio. Factor B was shown to have a minor influence on the variation but a large effect on cost. The SN ratio gain of the optimum condition was predicted to be 4.31 dB (Table 6).

5. Confirmation Test

A confirmation test revealed good reproducibility:

Gain predicted (dB): 4.31

Gain confirmed (dB): 5.78

Reproducibility (%): 134

The ultimate object of the project was, however, improvement of the productivity of booster manufacturing processes. To verify the optimized condition in manufacturing processes, a few hundred units were mass produced, and substantial improvement in the rolled throughput yield was realized.

6. Conclusions

The robust design method was used to solve a chronic brake booster problem. Using this highly efficient optimization process, considerable improvement in reducing the defect rate due to booster force variation was achieved. It would also be very helpful in enhancing productivity.

References

Genichi Taguchi, Subir Chowdhury, and Shin Taguchi, 2000. *Robust Engineering*. New York: McGraw-Hill.

Yuin Wu and Alan Wu, 2000. *Taguchi Methods for Robust Design*. New York: ASME Press; *ASI 18th Annual Taguchi Methods Symposium Proceedings*, Dearborn, MI.

This case study is contributed by Myoung-June Kim, Jun-Gyu Song, Chung-Keun Lee, Kyu-Yeol Ryu, and Ki L. Chang.