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QUALITY IMPROVEMENT FOR BRAKE JUDDER USING DESIGN FOR SIX SIGMA WITH RESPONSE SURFACE METHOD AND SIGMA BASED ROBUST DESIGN

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ABSTRACT–The problem of brake judder is typically caused by defects of quality manufacturing. DFSS (Design for six sigma) is a design process for quality improvement. DFSS will result in more improved but less expensive quality products. This paper presents an implementation of DFSS for quality improvement of the brake judder of heavy-duty trucks. Carrying out 5 steps of DFSS, the major reasons for defects of quality are found. The numerical approximation of the brake system is derived by means of the response surface method. Its quality for brake judder is improved by using the sigma based robust design methodology. Results are compared between the conventional deterministic optimal design and the proposed sigma based robust design. The proposed one shows that manufacturing cost may increase as the quality level increase. The proposed one, however, is more economical in aspect of the overall cost since the probability of failure dramatically goes down.

KEY WORDS : Brake judder, Design for six sigma (DFSS), Response surface method, Sigma based robust design, Brake torque variation (BTV), Deterministic optimization, Probabilistic optimization

1. INTRODUCTION

In six sigma quality management (Harry, 1997), sigma (σ) means standard deviation. Based on the probability density function of normal distribution, the probability within 6 is 99.9999998%. The quality of $\pm 6\sigma$ level satisfies the required specification of products with 99.9999998% reliability. It means 3.4 dpm (defect per million) quality in spite of consideration of $\pm 1.5\sigma$ shift due to unavoidable effects of noise factors in quality management. To achieve 6σ level quality, efforts in every stage for production such as design, manufacturing and inspection are required. It is important to establish proper design strategy in the early design stage because the decisions in design stage affect over 70% in the whole development process generally. Therefore the application of DFSS (Design for Six Sigma) concepts is required from the early design stage in order to get a robust design which provides better quality.

A recently developed brake system with an aluminum wheel of heavy-duty trucks had serious brake judder problems reported. The problem of brake judder is typically caused by quality defects in every stage for production. These quality defects, however, can't be controlled deterministically and requires a design considering uncertainties. These uncertainties are called noise factors that a designer can't fully control. The use of deterministic optimization algorithms is not sufficient in handling such a problem with noise factors due to its deterministic feature. Therefore, a stochastic approach has to be applied to improve the quality problems with noise factors. If, in manufacturing process, there are noise factors, then the probability of the production of defected products goes up. Therefore robust design method must be utilized to meet the required quality level if there exist a noise factor. One of robust design methods is Taguchi robust design (Ross, 1998). Taguchi method has been used for relatively long time, while reliability based optimal design method (Choi *et al.*, 1996) is used recently. In these days the research of sigma based robust design (Koch *et al.*, 2001) is being done and the results of study and applications begin to be shown in few areas which are closely related with the sigma based quality management such as the 6-sigma quality control.

In this paper, we implement DFSS with the response surface method and sigma based robust design method in order to improve the quality of brake judder problem of heavy-duty trucks. The procedure of DFSS consists of 5 steps: In the first step (Define), quality defects, that is,

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CTQ (Critical to Quality) will be examined from the research regarding the phenomena of brake judder problem in heavy-duty trucks. In the second step (Measure), they will be measured and computed. In step 3 (Analysis), the analysis of the measurement will show major reasons for the quality defects. Then design variables will be determined and the approximated model by means of the response surface method will be built. In step 4 (Improve), the optimal design will be obtained from the deterministic optimization approach. Then the obtained optimal design was analyzed by a stochastic approach considering design tolerances because the brake judder problem is sensitive to design tolerance. This analysis will provide the quality level of the deterministic optimal design. In the final step, if the optimized design shows low quality level, a robust design will be searched, which can satisfy the required quality level, such as, six-sigma one. A commercial software providing process integration and design optimization, iSIGHT (iSIGHT, 2001) was used in a part of the research described in step 4 and step 5.

2. THEORETICAL BACKGROUND

2.1. Sigma Based Robust Design

Optimal design can be categorized as deterministic optimal design and stochastic one. The deterministic one is formulated like Equation (1).

Minimize $F(\mathbf{x})$ (1.a)

Constraint to $G_j(\mathbf{x}) \le 0,\ j = 1, \ldots, Ng$ (1.b)

$x_{Li} \le x_i \le x_{Ui},\ i = 1, \ldots, Nx$ (1.c)

Design variables $\mathbf{x} = (x_1, x_2, \ldots, x_{Nx})^T$

In Equation (1), $F(\mathbf{x})$ is an objective function, $\mathbf{x}$ is a vector of design variables with the number of Nx. Equations (1.b) and (1.c) means constraint conditions. The ranges in design variables are described in the Equation (1.c). x_{Ui} and x_{Li} mean the upper and low limit value of a design variable x_i, respectively. $(x_i)^T$ means the transpose matrix of a column matrix (x_i). Generally, the result of deterministic optimal design is located along the border of feasible region where the design satisfies the constraint conditions. Someone describes it as walking along the edge of cliff. Therefore, when a design set by deterministic optimization method is used to build real products, it tends to provide defected products because there are several uncertainties - tolerance, material properties, and so on - in design, testing and manufacturing. These will affect quality of products and make it easy to overstep the border.

To make up the problem, the design minimizing the probability of failure in spite of uncertainties is requested. The one of probabilistic design methods, sigma based robust design (Koch *et al.*, 2001) is introduced in Equation (2).

Minimize $F^*(\mathbf{x}, \mathbf{p})$ (2.a)

Constraint to $G_j^*(\mathbf{x}, \mathbf{p}, n) \le 0,\ j = 1, \ldots, Ng$ (2.b)

$x_{Li} \le x_i \le x_{Ui},\ i = 1, \ldots, Nx$ (2.c)

$p_{Li} + n\sigma_{pi} \le \mu_{pi} \le p_{Ui} - n\sigma_{pi},\ i = 1, \ldots, Np$ (2.d)

Design variables $\mathbf{x} = (x_1, x_2, \ldots, x_{Nx})^T$

Noise variables $\mathbf{p} = (p_1, p_2, \ldots, p_{Np})^T$

$p_k \sim \xi(\mu_k, \sigma_k^2),\ k = 1, \ldots, Np$

In Equation (2), $F^*(\mathbf{x}, \mathbf{p})$ is a probabilistic objective function. $\mathbf{p}$ is a vector of noise variables with the number of Np. The k-th variable p_k have probabilistic distribution $\xi(\mu_k, \sigma_k^2)$, of which μ and σ means the mean value and the standard deviation of the probabilistic distribution, respectively. Equation (2.b) means probabilistic constraint conditions. Equations (2.c) and (2.d) are constraint conditions of design variables and noise variables, respectively. The number n in Equations (2.b) and (2.d) is the required sigma level of quality.

2.2. Brake Judder of Heavy Duty Truck

The brake judder of drum brake system is a kind of abnormal vibration caused by resonance in vehicle system due to excitation of BTV (Brake Torque Variation) caused by friction between linings and a drum at braking. It is categorized by the reason of BTV: mechanical judder and thermal judder. The main source of BTV for mechanical judder is due to local concentration of friction forces between the lining and the drum. Defects of a drum from manufacturing or quality inadequacy of each component, for instance, oversize, barrel shape, out-of-round, eccentricity, bell-mouth, taper, etc, affect large effect on local concentration of friction forces and occurrence of BTV. Lately, almost no problems from components are reported because of performing strict quality management for each component. Mechanical judder problems of drum brake system, however, are caused by defects that occurred when a drum is assembled with other components, such as, a wheel and a hub. For an example, the major problems after assembly process are eccentricity and static deformation of a drum. In this case, the fundamental frequency of harmonic excitation of BTV has the 1st and 2nd orders of wheel rotation.

3. DFSS FOR BRAKE JUDDER OF HEAVY DUTY TRUCK

The procedure of DFSS(Design For Six Sigma) consists of 5 steps described in Figure 1.

3.1. Define

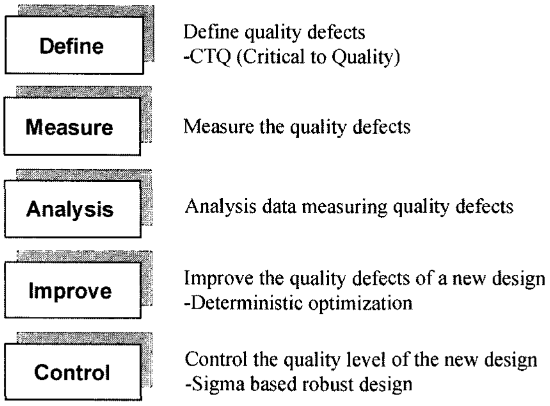
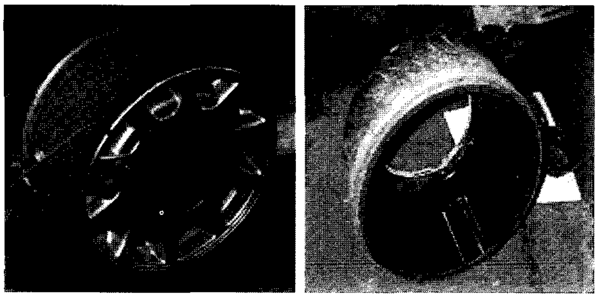


Figure 1. DFSS procedure.



(a) Aluminum wheel (b) Drum

Figure 2. Wheel and drum.

In this step, quality defects in brake system will be defined by analyzing the phenomena of brake judder of the heavy-duty truck with 24 ton carriage capacity. This brake system is equipped with recently developed aluminum wheels shown in Figure 2.

The major characteristics of this brake judder problem are following.

(1) No clear relationship to heat.
(2) Mainly occurred with 0.3G (Gravity) braking and condition loaded over GVW (Gross Vehicle Weight) at speed of 60 Km/h~80 Km/h and on downhill with 7% slope.
(3) Occurred with acceptable components; wheel, drum and hub, even though those components satisfy major design requirements such as run-out, flatness, concentricity, perpendicularity, unbalance and so on.
(4) Mainly occurred with the aluminum wheel specification and occasionally occurred with the steel one at overloaded condition over GVW(Gross Vehicle Weight).
(5) In addition, vibration characteristics at the 1st axle of the truck with judder problem at braking are shown as a waterfall diagram in Figure 3. It shows that the 4th order of wheel rotation is the fundamental frequency of the harmonic vibration.

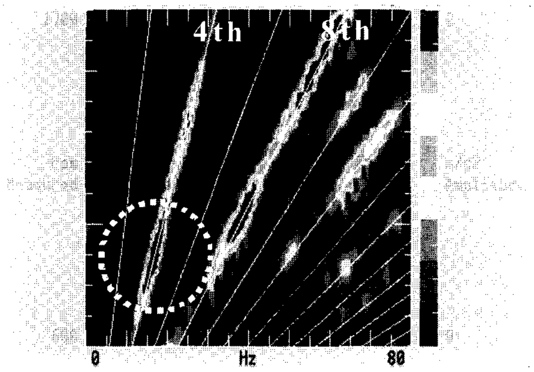


Figure 3. Waterfall diagram of the brake judder vibration.

Based on the phenomena of the brake judder problem described above, followings are deduced: this judder problem is a mechanical judder from the fact (1), it occurs when excessive loads are applied on the front axle from the fact (2), it is not related with defects of only a component from the fact (3) and its caused by the deformation of brake system due to the use of an aluminum wheel from the fact (4). Especially, the fundamental frequency of BTV is generated along the 4th order of wheel rotation from the fact (5). Therefore reasons different from its previously reviewed one in ch2.2 are expected.

In this step, quality defects that cause unwanted phenomena are assumed and verified in the next step (Measure) by experiments and computer-aided analyses. Figure 4 shows the concept of the assumed quality defects. The aluminum wheel might be deformed because of excessive road loads, which may yield bad effects on the flatness of the wheel disk. It finally should cause the elliptic deformation of a drum.

If so, the distribution of friction forces on the drum would be abnormal like Figure 5b rather than desirable shown in Figure 5a. In the case shown in Figure 5(b),

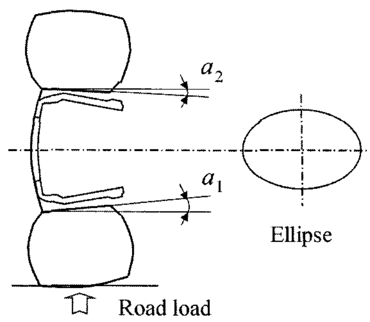
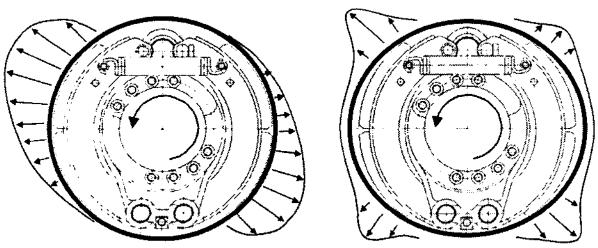


Figure 4. Drum deformation.



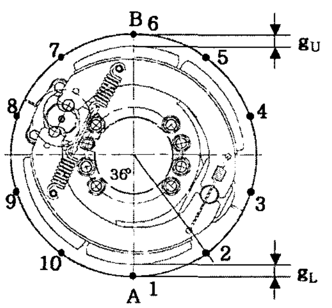
(a) Small deformation (b) Large deformation

Figure 5. Distribution of friction forces with drum deformation.

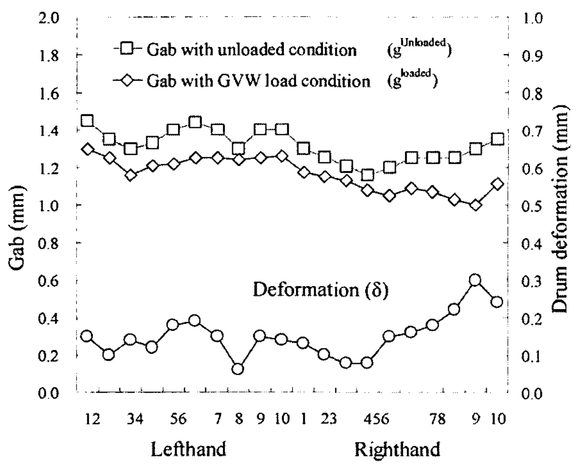
friction forces are concentrated on local area on contact surfaces and the amplitude of BTV is increased. Its coupled with the dynamic deformation of drum simultaneously according to the truck movement. Finally, the fundamental frequency of harmonic excitation of BTV is generated at the 4th order of wheel rotation.

3.2. Measure

In this step, the assumption considered in the previous step, Define is verified. The deformation of a drum due to applied loads is measured experimentally. Then, the deformation of a drum according to wheel specification and load condition is computed analytically.



(a) Measuring points



(b) Results

Figure 6. Vehicle test of drum deformation.

3.2.1. Vehicle test

To investigate effects due to applied loads, the deformation of a drum of the left and right hand side of the first axle is measured by using a full vehicle with the steel wheel specification. The gaps between linings and a drum at 10 measuring points per a drum are measured for two cases, i.e. unloaded case and loaded case with GVW. The deformation of a drum is calculated from the gaps as follows;

$$\delta_i = g_i^{unloaded} - g_i^{loaded},\ i=1,\ 20 \tag{3}$$

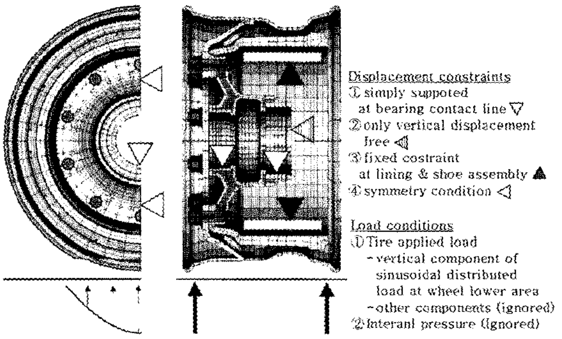
where $g_i = g_{Ui} + g_{Li}$

In Equation (3), δ_i is the deformation of a drum measured at the i-th measuring point. $g_i^{unloaded}$ and g_i^{loaded} are gaps of the i-th measuring point with respect to load conditions, respectively. g_{Ui} and g_{Li} are upper and lower gaps with respective to the i-th measuring points, respectively. The gap is the shortest distance between the drum and the assembly of shoe and lining.

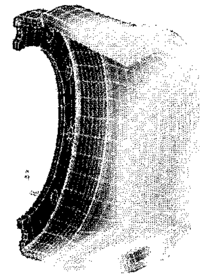
Statistical process of test results shows that GVW load generate the deformation of average, 0.151 mm and standard deviation, 0.05775 mm.

3.2.2. Finite element analysis

In the critical condition when brake judder occurs over GVW and 0.3G braking at 7% downhill, much bigger load due to inertia effect and slope of road is applied to the 1st front axle than static load. The measurement of the deformation of a drum, therefore, is required essentially. However, it's very difficult to measure the deformation of a rotating drum in an actual vehicle. In this research we use computational analyses for this condition. At the first, FEA (Finite Element Analysis) model for a wheel, drum, hub and assemblies of a lining and a shoe are built. Then experimental mode analyses are used for modal correlation of components. The whole assembled FEA model is built like Figure 7a. The contacts between components are modeled by contact boundary conditions. Gaps between each component are determined by tolerance given in blueprints. The assembled FEA model is correlated by comparing results of computational vibration analysis with those of vibration test. After assigning boundary conditions and contact conditions defined on the assembled FEA model as Figure 7a, non-linear static analysis was performed to calculate the deformation of drum. The deformed shape of a drum is shown in Figure 7b and the deformation value is 0.149 mm. The experimental result of Figure 6 shows that the average value of experiments is 0.151 mm.



(a) Finite element model and boundary conditions

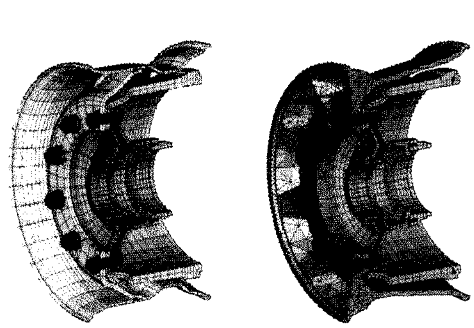


(b) Magnified deformation shape of a drum

Figure 7. Finite element model and drum deformation.

This computational analysis, therefore, provided an accurate result. Additionally, calculation of distribution of friction forces between a drum and linings shows that a deformed drum makes concentration of friction forces on local areas as shown in Figure 5(b).

It's identified that a drum is deformed by load applied on a wheel. New questions are raised; "How much critical load will cause brake judder problem? How much deformation of a drum will occur when the critical load applied? Why does the aluminum wheel specification has judder problem frequently but the steel one rarely?". In this section, efforts to find these answers will be described by comparing structural characteristics alone wheel specifications. Figure 8 shows the assembled FEA model according to the wheel specification. Their



(a) Steel wheel (b) Aluminum wheel

Figure 8. Finite element model of the assembly.

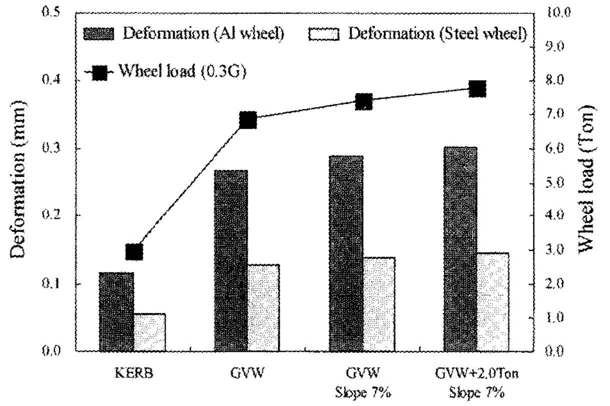


Figure 9. Wheel load and drum deformation.

boundary conditions are same as the previous calculation as shown in Figure 7a. The calculated wheel load when 0.3G braking and deformation of each drum are shown in Figure 9. The critical load causing brake judder problem on the truck with the aluminum wheel specification was 7.4175 ton. And then, the deformation of a drum in the aluminum wheel specification is 1.68 times bigger than that of a steel one at the critical condition, that is, 0.3G braking on 7% downhill with GVW load.

3.3. Analysis

In this step, the main reasons of the defect identified in the previous step, Measure a drum with the aluminum wheel is deformed more than one with the steel wheel under the same condition - is investigated. Then major design variables are determined and approximation models are built using the response surface method (Myers *et al.*, 1995; Lee *et al.*, 2002). Followings are the main reasons.

3.3.1. Lack of flatness stiffness of Al wheel

The comparison between flatness stiffness and radial

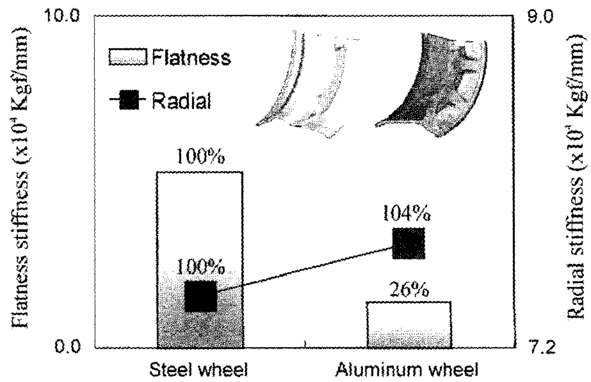


Figure 10. Comparison of flatness stiffness of wheels.

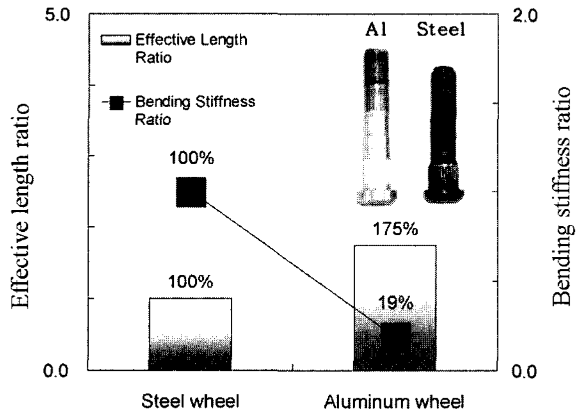


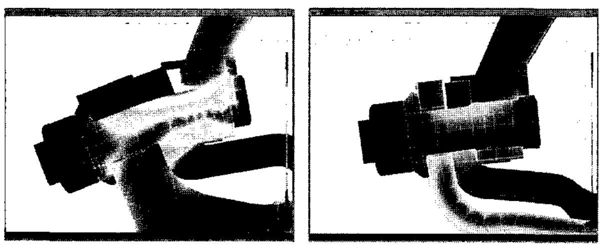
Figure 11. Comparison of bending stiffness of stud bolts.

stiffness of wheels by using 1/4 model is shown in Figure 10. It shows that the radial stiffness of aluminum wheel is 104% of one of steel wheel comparably. But the flatness stiffness of the aluminum wheel is 26% of one of the steel wheel. The flatness stiffness of the aluminum wheel, therefore, has worse than one of the steel wheel under the same load condition.

3.3.2. Lack of bending stiffness of stud bolt for Al wheel specification

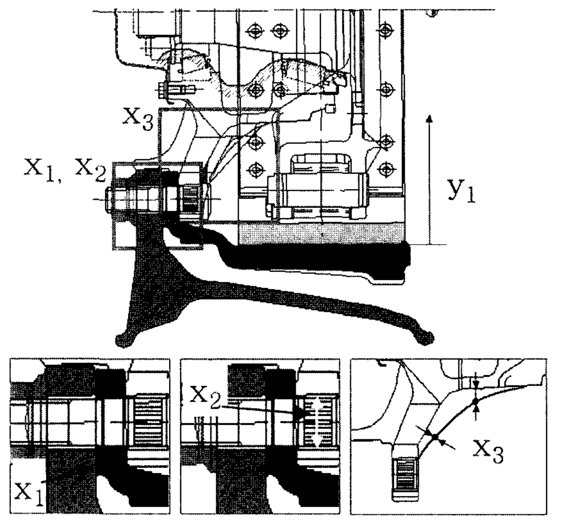
The bending stiffness of the stud bolt in aluminum wheel specification is reduced by 19% compared with one of the steel wheel specification due to increase in length shown in Figure 11. It causes larger deformation at the stud bolt joint in the assembly.

These two reasons cause bigger changes in the deformation of a drum with the aluminum wheel specification than that with the steel one. These changes rise deformation at the neck of a drum as shown in Figure 12 and then result in increase of deformation at the mouse of a drum as shown in Figure 7(b). The deformation of a drum with the aluminum wheel specification is increased by 227% compared with one with the steel wheel specification.



(a) Aluminum wheel (b) Steel wheel

Figure 12. Comparison of magnified deformation shape of the stud bolt joint.



(a) Design variables

x_1 : The step distance of a drum disk surface
x_2 : Diameter increment of stud bolt
x_3 : Distance from the reference hub section to two control points of a spline curve for reinforce rib
(b) Response variables
y_1, y_2 and y_3 : The ratio of response of aluminum wheel design with respect to that of steel wheel design
y_1 : The ratio of deformation in the drum mouth
y_2 : The ratio of Von-Mise maximum stress in drum
y_3 : The ratio of Von-Mise maximum stress in bolt
y_4: The ratio of mass in modified design with respect to that in initial design

Figure 13. Design and response variables.

Based on the previous analyses, the increase of wheel flatness stiffness and decrease of the length of stud bolt is required to reduce the deformation of a drum with the aluminum wheel specification. But it requires high cost to modify the specification of aluminum wheel. The above suggestions, therefore, cannot be applied. So other parts have to be considered to change design. The three major design variables, x_1, x_2, and x_3 are selected according to analyses of DOE (Design of Experiments). In addition, the following four outputs are selected as response variables as shown in Figure 13. The response variables y_1, y_2 and y_3 are defined as a ratio of the values from the aluminum wheel specification to those from the steel wheel specification because performance of the steel wheel specification could be a target for the optimal design of the aluminum wheel specification. In the other side, the response y_4 is set as the ratio of mass in the final design to that in the initial design because this make a designer figure out clearly the change of mass in optimization processes. The response surface method with the central composite design method (Myers *et al.*, 1995) was used to approximate these response variables.

In the central composite design method, design variables are considered by 3 levels, [−1, 0, 1] and total 15 finite element analyses ($2^3 + 2*3 + 1 = 15$) are performed with three design variables. The 2nd order polynomial response surface equations (4)~(7) are built based on the result of response values from the simulation. The R^2 values for responses are 97.7%, 93.2%, 96.4% and 100.0% respectively.

$$y_1 = 2.07978 - 0.166709\,x_1 + 0.338831\,x_2 - 0.0612206\,x_3 + 0.00391889\,x_1^2 - 0.228748\,x_2^2 + 0.00511889\,x_3^2 + 0.00228968\,x_1 x_2 - 4.16667\text{E-}06\,x_1 x_3 + 0.0000912698\,x_2 x_3 \quad (4)$$

$$y_2 = 0.904690 - 0.0509178\,x_1 + 0.143606\,x_2 + 0.00967222\,x_3 + 0.0157178\,x_1^2 - 0.0726127\,x_2^2 - 0.00241222\,x_3^2 - 0.0517500\,x_1 x_2 + 0.00816750\,x_1 x_3 + 0.00948810\,x_2 x_3 \quad (5)$$

$$y_3 = 1.12497 - 0.0484522\,x_1 - 0.289844\,x_2 - 0.00152722\,x_3 + 0.00712222\,x_1^2 + 0.0982363\,x_2^2 - 0.000467778\,x_3^2 + 0.0126429\,x_1 x_2 - 0.000905000\,x_1 x_3 + 0.00438095\,x_2 x_3 \quad (6)$$

$$y_4 = 1.00002 - 0.000111161\,x_1 + 0.0000973222\,x_2 + 0.00165047\,x_3 + 1.993919\text{E-}06\,x_1^2 + 0.0000452136\,x_2^2 - 3.68875\text{E-}05\,x_3^2 + 3.560569\text{E-}06\,x_1 x_2 + 7.477195\text{E-}07\,x_1 x_3 + 3.560569\text{E-}06\,x_2 x_3 \quad (7)$$

3.4. Improve

In this step, a deterministic optimization, to improve deformation and stress in the aluminum wheel specification up to those in the steel wheel specification while to minimize total mass of brake assembly", will be performed by using the response surface models built in the previous step. Then the analysis of quality level of this design will be done, which is varied due to tolerance in manufacturing process and so on. If the quality cant meet the required sigma level in this step, for example 6-sigma, the robust design search using a stochastic approach will be performed in the next step, control. The formulation of the optimization problem is as follows;

Minimize Mass ratio y_4
Constraint to
Drum deformation ratio $y_1 \le 1.0$
Drum stress ratio $y_2 \le 1.0$
Bolt stress ratio $y_3 \le 1.0$
and
Drum disk step height $0.0 \le x_1 \le 10.0$
Bolt diameter increment $-2.1 \le x_2 \le 2.1$
Hub control point $-5.0 \le x_3 \le 10.0$
with initial values of x : $\mathbf{x}_0$

$\mathbf{x}_0 = (x_1, x_2, x_3)^T = (0.0, 0.0, 0.0)^T$

The initial values of design variables are values of the current design with the aluminum wheel specification. The response variables are calculated from the relationship Equations (4)~(7) between design and response. An exploratory optimization algorithm, SA (Simulated Annealing) and a numerical optimization method, MMFD (Modified Method of Feasible Directions) are used sequentially as optimization strategy to explore the design space efficiently. By the SA algorithm, the exploration is driven globally then the MMFD is implemented to pick the best point locally located around the best point from the previous exploration. The result of this optimization exploration is shown in 'Mean' column of 'Deterministic optimal design' in Table 1. After decision of the deterministic optimal solution, the analysis of quality level was done. It's because the quality is changed due to uncertainties such as tolerance of manufacturing. The result of sigma analysis of the optimal design is shown in 'Quality level' column of 'Deterministic optimal design' in Table 1. Monte Carlo Simulation (Saliby, 1990) is used for this analysis. In the stochastic analysis the tolerance of design variables can't be controlled by designers but can be considered by using the probabilistic distribution of each tolerance. Here, all parameters are noise factors as well as design variables described by normal distribution with mean and standard deviation (5% of optimum values respectively). The standard deviation values are based on the process capabilities of the related company. Among response values in Table 1, quality level of y_1 shows 0.7σ and it is very poor compared with the required level of quality, 6σ.

3.5. Control

In this step, the sigma based robust design will be described to achieve the required quality level even if there are noise factors such as tolerances. The formulation of this robust design is as follows;

Minimize Mass ratio $w_\mu \mu_{y4} + w_\sigma \sigma_{y4}$
Constraint to
Drum deformation ratio $\mu_{y1} + 6\sigma_{y1} \le 1.0$
Drum stress ratio $\mu_{y2} + 6\sigma_{y2} \le 1.0$
Bolt stress ratio $\mu_{y3} + 6\sigma_{y3} \le 1.0$
and
Drum disk step height $n\sigma_{x1} \le \mu_{x1} \le 10.0 - n\sigma_{x1}$
Bolt diameter increment $-2.0 + n\sigma_{x2} \le \mu_{x2} \le 2.1 - n\sigma_{x2}$
Hub control point $-5 + n\sigma_{x3} \le \mu_{x3} \le 10.0 - n\sigma_{x3}$
with initial values of x : $\mathbf{x}_0$

$\mathbf{x}_0 = (x_1, x_2, x_3)^T = (6.76455, 2.1, -1.88484)^T$

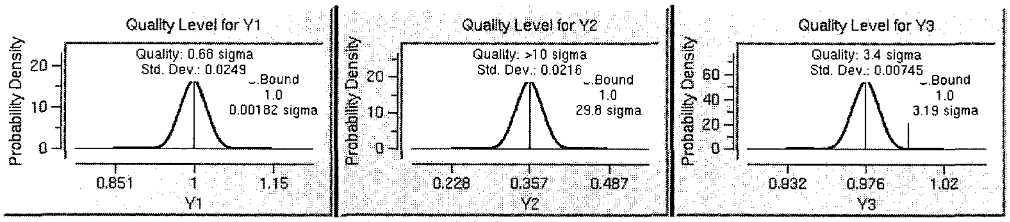
Random variables : $x_1 \sim N(\mu_{x1}, (\mu_{x1} * 0.05)^2)$
$x_2 \sim N(\mu_{x2}, (\mu_{x2} * 0.05)^2)$
$x_3 \sim N(\mu_{x3}, (\mu_{x3} * 0.05)^2)$

Quality level : $n = 6$
Weighting factors : $w_\mu = w_\sigma = 1.0$

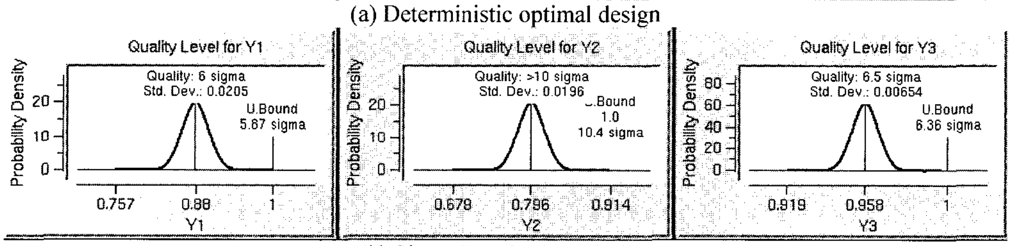
Table 1. Deterministic optimal design and sigma based robust design.

Design variable		Base line design	Deterministic optimal design with sigma analysis				Sigma based robust design			
			Mean	Standard deviation	Quality level (σ)	DPM	Mean	Standard deviation	Quality level (σ)	DPM
Design (Random)	x_1	0.00	6.76455	0.33823	>10.0		7.02802	0.35140	>10.0	
	x_2	0.00	2.10000	0.10500	0.7		1.86454	0.09323	6.0	
	x_3	0.00	-1.88484	0.09424	>10.0		1.68366	0.08418	>10.0	
Response	y_1	2.07978	0.99995	0.02488	0.7	499,273	0.87991	0.02047	6.0	2.2E-03
	y_2	0.90469	0.35721	0.02156	>10.0	0	0.79625	0.01956	>10.0	0
	y_3	0.97824	0397625	0.00745	3.4	719	0.95839	0.00654	6.5	9.9E-05
	y_4	1.000	0.99655	0.00007	-	-	1.00242	0.00006	-	-

DPM : Defects Per Million



(a) Deterministic optimal design

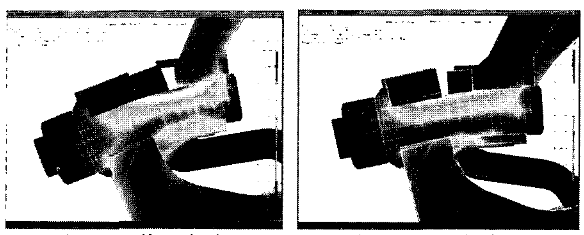


(b) Sigma based robust design

The objective function is described as the linear combination of mean value and standard deviation of total mass of the assembly. In this case, parameters are considered as design variables and noise variables. That's why sigma level was set on design variables also. The required sigma level, 6σ is considered as a constraint and this constraint restricted the result of design variables and response variables in the robust optimization. Sampling algorithm is Monte Carlo Simulation due to its accuracy and the MMFD algorithm with initial values of results from the deterministic optimal design is used to explore the design space to find the design that meet six sigma quality level. Table 1 shows results of this search. According to the deterministic optimization approach, the mass of the assembly is reduced to 99.66% of initial design but sigma level of the quality is 0.7σ, i.e. over 490,000 defected products per one million productions. On the other side, the robust design with six sigma level quality shows less than one DPM (Defects Per Million). The mass of the assembly is increased by 0.242% over the baseline design.

4. VERIFICATION OF ROBUST DESIGN

Figure 14 shows the comparison of deformation shape in the stud bolt joint. It shows the robust design has little deformation of a drum although it has large deformation



(a) Baseline design (b) Robust design

Figure 14. Comparison of magnified deformation shape of the stud bolt joint.

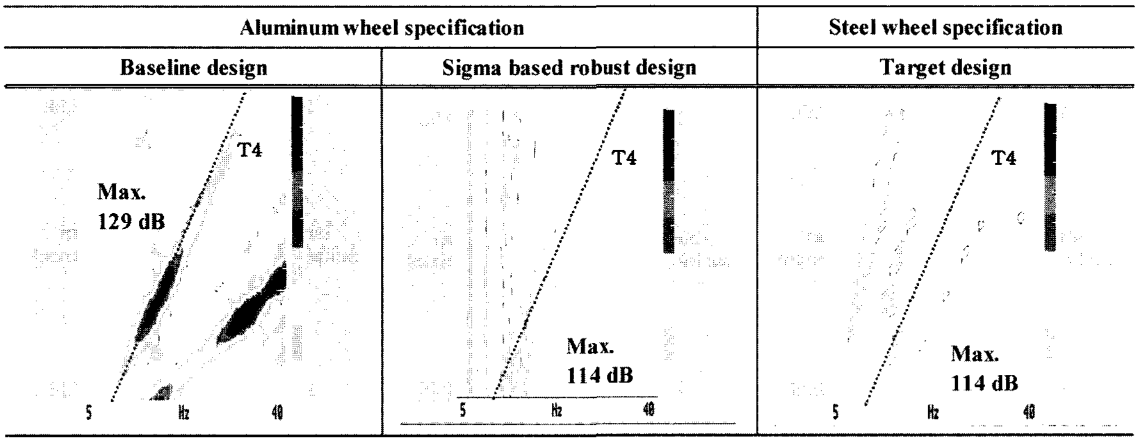


Figure 15. Comparison of waterfalls of brake judder vibration.

of wheel. The deformation of drum in the robust design is decreased by 34% compared with one in the baseline design.

We measured the vibration level between the baseline design and the robust one by using the truck in field under brake judder condition. Figure 15 shows that the vibration level of the proposed robust design is reduced by 15dB compared with one of the baseline design. It is same as one of the target design, that is, the steel wheel specification. These days, no judder problems are reported from customers.

5. CONCLUSIONS

For the mechanical judder of drum brakes in heavy-duty trucks, DFSS with the response surface method and sigma based robust design is applied to obtain a robust design and its results are as follows;

(1) The major quality defect of brake judder problem is due to the deformation of a drum under braking. It comes from the lack of flatness stiffness in the aluminum wheel and the lack of bending stiffness of the stud bolt.

(2) The application of deterministic optimal design helps to find the most economic design but, in case of the real manufacturing process with noise factors such as tolerance, a product corresponding to the deterministic design shows very poor quality with low sigma level.

(3) The sigma based robust design was obtained, which is the design satisfying the required quality level in spite of tolerances of design variables. The robust design is affirmed that it minimizes deformation of the drum and stress of components although there are tolerance, bad flatness property of the aluminum wheel and weak bending stiffness of the stud bolt.

(4) The brake judder is one of quality problems that are sensitive to tolerance in manufacturing. Therefore it is required the design in which the quality variation due to such uncertainties is considered. The sigma based robust design shows that the manufacturing cost may increase as the quality level increase. However, because the probability of failure dramatically goes down, its more economical in aspect of overall cost.

REFERENCES

Choi, K. K., Yu, X. and Chang, K. (1996). A mixed design approach for probabilistic structural durability. *6th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization*, Bellevue, WA., 785-795.

Harry, M. J. (1997). *The Nature of Six Sigma Quality*, Motorola Univ. Press., Shaumburg, Illinois, 27–42.

iSIGHT Users Manual, Ver. 6.0, (2001). Engineous Software, Inc., Morrisville, NC.

Koch, P. N. and Gu, L. (2001). *Addressing Uncertainty using Probabilistic Design Environment*, Engineous Soft- ware, Inc., Morrisville, NC., 1–14.

Lee, S. B., Park, J. R. and Yim, H. J. (2002). Numerical approximation of vehicle joint stiffness by using response surface method. *Int. J. of Automotive Technology* **3, 3,** 117–122.

Myers, R. H. and Montgomery, D. C. (1995). *Response Surface Methodology*, John Wiley & Sons Inc., New York, 127–189.

Park, S. H. (2001). *Modern Design of Experiment*, Daeyoung, Inc., Seoul, 575–625.

Ross, P. J. (1998). *Taguchi Techniques for Quality Engineering*, McGraw Hill. New York, 227–289.

Saliby, E. (1990). Descriptive sampling: A better approach to monte carlo simulation. *J. Opl. Res. Soc.* **41, 12,** 1133–1142.