Multi-domain Modeling and Robust Design of Hydraulic Shock Absorber

Peng Manlong[1], Ling Feng[1, 2], Fu Wenkui[1], Zhang Yunqing[1]
1. Huazhong University of Science &Technology, Wuhan, China
2. Ordnance Noncommissioned Officer School, Wuhan, China
e-mail: pengmanlong126@yahoo.com.cn

***Abstract*—In this paper, a suspension with spring and Hydraulic shock absorber model is presented with AMESim software. Hydraulic shock absorber model contains piston valve assembly, bottom valve assembly, rebound chamber, compression chamber, reserve chamber and so on. Then the optimal parameters of the Hydr-aulic shock absorber are determined using 6σ robust optimization method. Finally, the performance of original parameters, deterministic optimizing param-eters and robust optimizing parameters are compared. The result indicates the 6σ robust optimization method can greatly improve the property of the Hydr-aulic shock absorber.**

Keywords-Hydraulic shock absorber, Robust design, AMESim modeling

I. INTRODUCTION

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Hydraulic shock absorber(HSA) is one of the most important and complex elements in a vehicle suspension system. There are two approaches to modeling shocks, one is analytical modeling based on physical and geometrical data, the other is parametric modeling based on experimental data [1]. The parametric modeling is simply suitable for some certain situation.

There are some complex analytical HSA models developed by researchers, such as Lang' model [2] and Morman' model [3]. However, they are very complex thus merely be used in research. So it's very necessary to build a completely and simply model based on multi-domain. In this paper, a suspension with spring and HSA model was established based on AMESim, and 6σ robust optimization method was used to improve the property of the HSA.

II. THEORY OF ROBUST DESIGN

There are some methods to estimate reliability, such as Monte Carlo methods[4] and Reliability-based optimization methods. There is an additional method called Robust Design which can improve both the reliability and the standard deviation of the mean.

Two famous robust methods mostly used by researchers is Taguchi robust design and 6σ robust design. According to Dr. Taguchi[5], robustness is defined as "A state of insensitivity of the functional performance of a product or a process to variations in raw material, manufacturing processes and operating environment over its intended useful life".

Considering only a small amount of factors of robust design described in following sections, then the 6σ method is more suitable for this situation. Figure1 shows the basic optimization principal of 6σ method.

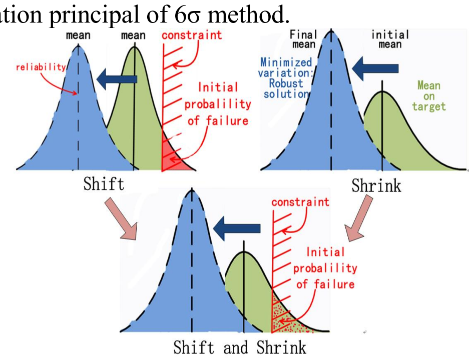

Figure 1. the basic optimization principal of 6σ method

6σ design is an optimization method which makes the mean and standard deviation of objective function as appropriate as possible. The optimization model can be expressed as:

$$\begin{aligned} &\text{Minimize: } F\left(\mu_y(x), \sigma_y(x)\right) \\ &\text{Subject to: } G_j\left(\mu_y(x), \sigma_y(x)\right) \le 0, j = 1, 2, \cdots, M \\ &x_{Li} + n\sigma_{x_i} \le \mu_{x_i} \le x_{Ui} - n\sigma_{x_i}, i = 1, 2, \cdots, N; \end{aligned} \quad (1)$$

Generally, F(x) is expressed as:

$$F = \sum_{i=1}^{L} \left(\frac{w_{1i}}{s_{1i}} \left(\mu_{yi} - T_i \right)^2 + \frac{w_{2i}}{s_{2i}} \sigma_{yi}^2 \right) \quad (2)$$

III. THE MODELING OF HYDRAULIC SHOCK ABSORBER

A. Physical structure

In working condition, the piston valve assembly and the bottom valve assembly are used. The fluid paths are shown in the Figure 2.

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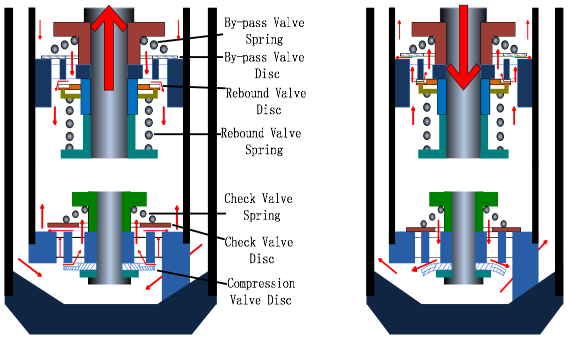

a. The rebound stage b. The compression stage

Figure 2. Two working conditions of the HSA

According to the structure described above, the piston valve assembly model and the bottom valve assembly model are built in AMESim software environment.

B. Piston valve assembly model

The structure of piston valve assembly is shown in Fig 3, and corresponding of piston valve assembly is shown in.

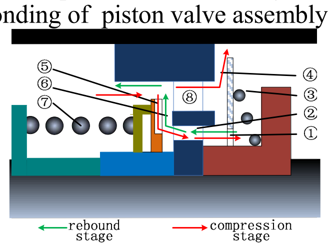

Figure 3. the structure of piston valve assembly

The throttle effect is simulated by a fixed hydraulic orifice signed '1' in Figure4.

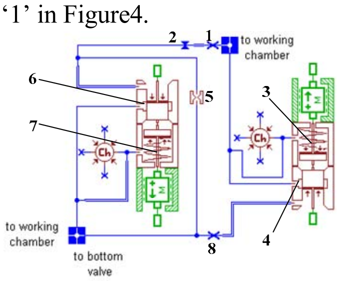

Figure 4. the model of piston valve assembly

C. Bottom valve assembly model

The bottom valve assembly includes two valves, the compression valve and the check valve.

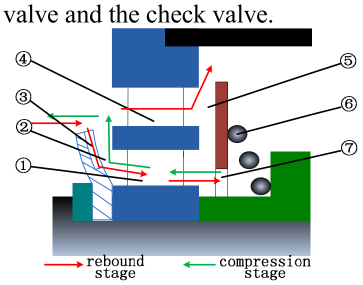

Figure 5. the structure of bottom valve

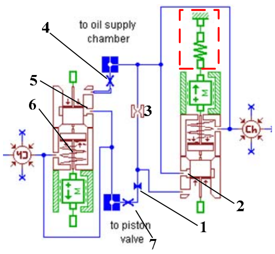

Figure 6. the model of bottom valve

The structure of the bottom valve is shown in Figure5 and the AMESim model is shown in Figure6. The part signed by red box in Figure6 is simulates the stiffness of compression valve disc, expressed as "PK" in following section.

D. The overall model

Figure7 shows a 1/4 vehicle model including the overall model of the HSA. Two valve assembly models mentioned above consist of the HSA model.

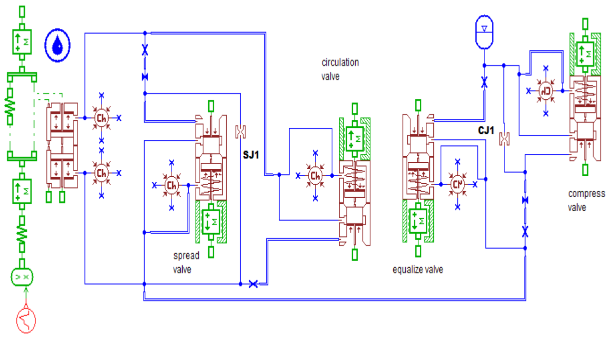

Figure 7. the 1/4 vehicle model

IV. DESIGN VARIABLE SELECTING

Variables are selected after researching HSA characteristic curves. Then they be used in sensitivity analysis. The 11 variables are shown in Table.1.

The input signal shown in Figure9(b) is translated from the standard pulse road by considering vehicle velocity. The velocity is 16Km/h， and the pulse road is shown in Figure9(a).

（a） （b）

Figure 8. the standard pulse road block and the input signal in AMESIM

The acceleration (oa), displacement (od) and force (of) between tire and road selected as the objective at sensitivity analysis. The results of sensitivity analysis is shown in Figure10.

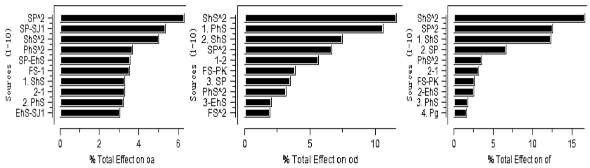

Figure 9. the effects of 11 variables on "oa", "od" and "of"

As is shown in in Figure 10, five variables have a great influence on this three objectives. They are SP, ShS, PhS, FS, EhS and Pg. The other factors shown in Figure10 is all consisted by these five factors. The five factors will be used as design parameters in robust optimization.

V. ROBUST OPTIMIZATION

In order to improve the performance of the vehicle ride comfort as far as possible, we take the vertical acceleration (acc) of bodywork as the objective. The working displacement is maintain within 0.1m, and the force between tire and ground is greater than 3kN. Then according to 6σ robust optimization method, the model is created as following:

$$\text{Minimize } \frac{W_\mu}{S_u}\mu_{acc}+\frac{W_\sigma}{S_\sigma}\sigma_{acc}$$

$$\text{Subject to } 6\sigma_{dis}\le\mu_{dis}\le 0.1-6\sigma_{dis};\ \mu_{force}\ge 3000+6\sigma_{force};\ 11+6\sigma_{SP}\le SP\le 17-6\sigma_{SP};$$
$$1.2+6\sigma_{ShS}\le ShS\le 5-6\sigma_{ShS};\ 1.3+6\sigma_{PHS}\le PhS\le 5-6\sigma_{PHS};$$
$$18+6\sigma_{FS}\le FS\le 24-6\sigma_{FS};\ 6+6\sigma_{FS}\le EhS\le 12-6\sigma_{FS};\ 2+6\sigma_{FS}\le Pg\le 8-6\sigma_{FS};$$
$$X_0=(SP,ShS,PhS,FS,EhS,Pg)^T=(14.8,4.4,1.76,22.1,8,4.5)^T;$$

The change of parameters in manufacturing and working are considered in all constraints. The standard deviation used in robust design is ±10%. Table 2 compared the valves and 6σ level.

The displacement and acceleration curves of bodywork in 1/4 vehicle model are shown in Figure11 and Figure12.

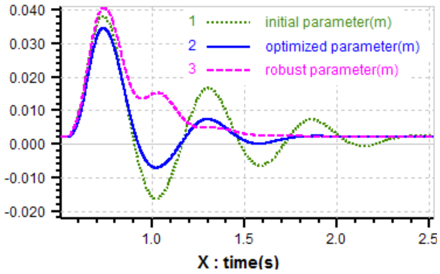

Figure 10. the displacement of bodywork with different parameters

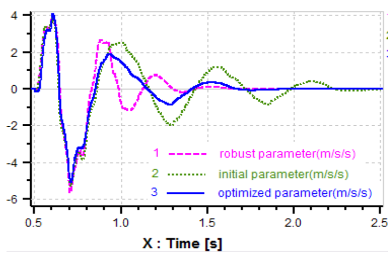

Figure 11. the acceleration of bodywork with different parameters

As is shown in these figures. 6σ robust optimization method cannot make all design parameters to achieve 6σ level. So this method is just a way to find a coordinate goal between the design objectives and the product reliability. The essence of this method is to find a point in design space to settle for optimized objective and reduce design risk. The σ level of certainty optimization is lower than robust method when the design parameters under the same standard deviation. Although there are some parameters not achieved 6σ level in robust optimization, the σ level is high and the product failure is a small probability event.

Human body have a certain sensitivity frequency to vibration. The bodywork is also own resonance frequency. So vibration research can not avoid in vehicle component design, especially for the HSA. Figure 13 shows the vertical acceleration power spectral density of bodywork.

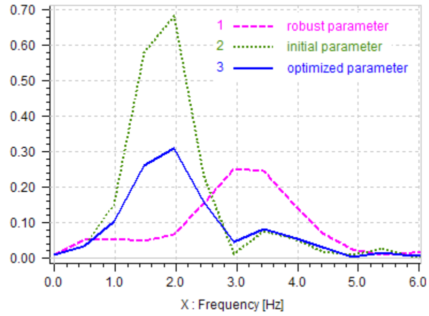

Figure 12. the bodywork's vertical acceleration power spectral density ($(m/s^2)^2/Hz$)

From the analysis of the acceleration power spectral density curves. Initial design and deterministic design make a large part of the vibration energy distributed mainly in 1~2.2Hz. Compared with it, the robust optimization makes the vibration energy distributed neither in human body's sensitivity frequency 0.05~0.5Hz and 4~12.5Hz nor in bodywork's resonance frequency 1~1.5Hz. This is very helpful to improve the ride comfort of vehicle.

VI. CONCLUSIONS

The 6 σ robust method is introduced to research a HSA in this paper. Some variables are selected by sensitivity analysis. The variation of these parameters is considered. The robust parameters are calculated by 6 σ robust optimization model. The σ level and performance curves of initial design, deterministic design and robust design are compared at last section. Compared with the deterministic method, the 6 σ robust method can increase the stability of HSA and greatly improve the ride comfort of the 1/4 vehicle model.

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TABLE I. THE VARIABLES

Parameters	**PK(N/mm)**	**SP(mm)**	**FS(mm)**	**PS(mm)**	**SPK(N/mm)**
indicated structure	Stiffness of compression valve disc	Diameter of rebound valve disc	Diameter of by-pass valve disc	Diameter of compression valve disc	Stiffness of rebound valve spring
PhS(mm)	ShS(mm)	EhS(mm)	SJ1(mm)	CJ1(mm)	Pg(bar)
Diameter of ① in Figure5	Diameter of ② in Figure3	Diameter of ④ in Figure5	Equivalent diameter of ⑤ in Figure3	Equivalent diameter of ③ in Figure5	Gas pressure of oil supply chamber

TABLE II. PARAMETERS VALUE AND Σ LEVEL

	Design parameters（σ level）						**Evaluation function**	
	SP	***ShS***	***PhS***	***FS***	***EhS***	***Pg***	***dis***	***force***
Initial	14.8 (5.42)	4.4 (0.69)	1. 76 (1.57)	22.1 (2.4)	8 (4.53)	8 (>=8)	0.038 (3.4)	3246.9 (2.8)
Deterministic	16.8 (3.86)	2.0 (2.46)	1. 45 (0.86)	23.4 (1.23)	9.21 (2.67)	7.5 (1.5)	0.035 (2.31)	3656.4 (1.48)
6σ robust (±10%)	12.6 (>=8)	3.2 (6.13)	2.1 (3.2)	20.1 (4.16)	8.84 (4.02)	6.54 (6.4)	0.042 (6.86)	3156.3 (5.78)