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Shape Optimization of Car Body Structure Based on Uniform Design Method

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***Abstract*—A finite element model for a domestic car-body is built. Based on the stiffness criterion,the stiffness sensitivity of the whole auto-body structure parts are analyzed under torsion and bending loads, Based on the results, the design of the structure and dimension of the body parts is optimized and the stiffness and sensitivity of the whole body is proved to be more reasonable. The Uniform Design method is used to arrange tests .The test results show after appropriate optimization the weight of the vehicle automobile body reduced form 301.5Kg to 292.6Kg when the anti-curving and anti-torsional rigidity of the autobody maintained invariable.**

***Keywords* — autobody ; sensitivity analysis ; shape optimization; FEA ; Uniform Design**

I. INTRODUCTION

The research of autobody lightweight technology is an important mainstream in the autobody design. By statictics it has proved that 0.2～0.3 litre oil per 100 km can be economized when the body mass is reduced 100kg. And a large amount of materials can be saved and manufacture cost can be decreased. Nevertheless, autobody as a kind of thin-walled member affect the whole automobile's performance、economy、comfort、security and stability. So the work of vechicle body design is very complicated, which is involved of quite more factors. In fact, it is a performance optimization control sytem study by using multi-discipline integration technique. In the study of structure shape optimization, sizing optimization and topology optimization, some theoretical work has been done by many domestic and overseas scholars. In the parameter (size) optimization aspect, from middle eighties of 20th century, the international researchers, such as Esping[1], Brainbant, Fleury[2], Bennett, Bokin[3], and Botkin etc[4] began to trying use integrative software system for optimization design. At the corresponding period, the domestic researchers Qian Lingxi etc[5-7] proposed an arithmetic of structure optimization, which was based on the Sequential Quadratic Programming(SQP), and a DDDU program system. Gu yuanxian, Cheng gengdong etc[8] absorbed the research production of structure optimization design theory, and worked out MCADS - computer aided structure optimization design software, which was adopted engineering structure design oriented practicality technique. The optimization arithmetic was ameliorated based on Sequential Quadratic Programming(SQP) and Sequential Linear Programming(SLP). In the topology optimization, a very important development in topology optimization has been acquired since Bendsoe etc[9] initiated the homogenization method for continuous structures. Successively optimization model such as homogenization model, density changed model, and thickness changed model etc have been carried out. These models basically make the structure's complaisance minimal as the aim function, and take volume upper limit as constraints. Though basically, a lot of valuable results from these models' research have been acquired. Evolutionary Structural Optimization (ESO method)[10-15] is a numerical method settled for various structure optimization problems, arisen since the recent years. The basic idea of ESO is that by slowly removing inefficient or low efficient element material, the residual structure evolves towards an optimum. However, the practical application on large and complex structure is can not be enough. In literature [16], a research is carried out on the optimal structure designing of thin-walled panel and the Successive Quadratic Programming (SQP) is used for optimization, and with the programmed OPTSHEET, a simplified FE model is created for the body structure, then a satisfactory result is obtained when calculating on it. In literature [17], the sensitivity analysis is carried out on the car body modal modification with commercial software ANSYS and a method is proposed on the improving of body parts. In literature [18], Taguchi method is used to optimize the body frame in the test study, and the cross-section parameters of body parts are modified so as to improve the torsion and bending stiffness of the whole body. In literature [19], applying ANSYS software with gradient method for the sensitivity analyze of the thickness of the auto-body panel under loading conditions and optimize the thickness of the body parts.

In this paper, the stiffness sensitivity of the whole auto-body structure parts are analyzed under torsion and bending loads, based on the results, optimize the design of the structure and dimension of the body parts, then the stiffness and sensitivity of the whole body is proved to be more reasonable. The test results show that the optimized body structure would be much lighter than the former one even under the same torsion and bending stiffness conditions.

II. THE MATHEMATICAL MODEL OF THE OPTIMIZATION OF THE AUTO-BODY STRUCTURE

The auto-body structure is composed of a series of complex thin-walled parts by welding, the technology of ultralight auto-body based on parameter optimization is to find the minimum thickness of the correlative components thereby achieve the minimum weight. However, this

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might lead to the largest stress of the auto-body structure significantly increase and the stiffness decline. Therefore, the following optimized mathematical model will be created according to the structure stress constraints:

To calculate the design variables t_1，t_2，…… t_N satisfy:

$$\begin{cases} MinW = \sum_{i=1}^{N} w_i \\ \sigma_{\max} < \sigma^* \\ t_i^{\min} \le t_i \le t_i^{\max} \end{cases} \quad \text{i=1，2，……N} \qquad (1)$$

where t_i is the thickness of the i-th component，w_i is the mass of -th component，W is the total mass of the structure，σ^* is the allowable stress of the structure，$t^{\min}$ and $t^{\max}$ are the allowable minimum and maximum thickness of the i-th component respectively，N is the number of components of the whole auto-body.

Before establishing the FE model, the whole structure and layout of the thin-walled body panel shall be taken into considered and to determine the element modes geometric parameters of each element. Due to the complicated structure of the thin-walled panel, which normally consists the thin-walled shell and frame, so a group of various element modes can be applied and also the geometry dimension of each element will not be identical. According to the designing standards and requirements of thin-walled body panel, the geometry dimensions of each element can be determined with reference to the relevant examples. In this paper, the auto-body of homemade X type car is analyzed using FE method with MSC.NASTRAN, the model of auto-body composed of 252984 nodes and 240272 elements, which is presented in Fig. 1:

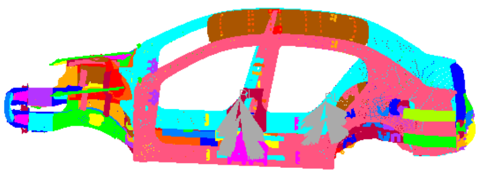

Figure 1. Fig.1The FE model of original autobody

The loads acting on the auto-body are different. Bending and torsion loads are the main parts, while others are much lower such as the vertical and lateral load, which are not considered in this calculation. The bending loads are mainly from staff, seat, deadweight, decorations and equipments. The weights of the decorations and equipments are uniformly distributed to each node by calculating each element, while the weights of staff and seats are equivalent distributed to the relevant nodes of the floor according to the seats' locations. The torsion loads are mainly caused by the nonsymmetrical supports from uneven ground, so much as that the diagonal wheels ride on the projections while the other wheel hangs in the air, and this may cause strong torsion on the auto-body.

The model in the present article is calculated on the PC system. A comparison of the calculated results with FE method and the test results shows that the model for auto-body is reasonable and the analyzed data of the structure coincide well with the test ones. The calculation results with FE method are presented in Fig. 2 and Fig. 3:

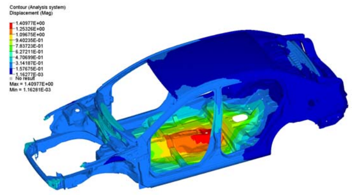

Figure 2. Fig. 2 The calculation results under bending load case

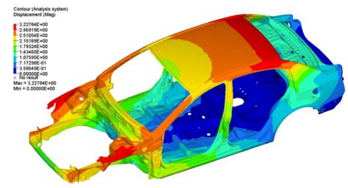

Figure 3. Fig. 3 The calculation results under torsion load case

III. STRUCTURE OPTIMIZATION CRITERION

For the static structure optimization problem, the general optimization criterions are stiffness criterion, full stress theory, displacement sensitivity criterion, stress sensitivity criterion and so on. This paper used the stiffness criterion for the problem.

In the finite element analysis, the static characteristic of the structure is described by the below equation:

$$[K]\{u\} = \{P\} \qquad (2)$$

Here, [K]is the collectivity stiffness matrix. $\{u\}$ is the entirety displacement vector, and $\{p\}$ is the node load vector.

The whole strain energy of the structure is defined as:

$$C = \frac{1}{2}\{P\}^T\{u\} \qquad (3)$$

It is often served as the contrary measurement of the collectivity stiffness of the structure, which is also named as evenness flexibility. Obviously, to make the structure's collectivity stiffness maximal means equivalent to make the structure' strain energy minimal.

Considering remove the i_th element from the structure, which is formed by N elements, the alteration of collectivity stiffness matrix is given below:

$$[K] = [K^*] - [K'] = -[K^i] \qquad (4)$$

Where, $[K^*]$ is the collectivity stiffness matrix with the i_th element removed. $[K^i]$ is stiffness matrix of the i_th element. Given that the removed i_th element has little impact on the load vector $\{p\}$, and ignore the high_order terms,we can educe the displacement alteration from the equation (2).

$$\{u\} = -[K]^{-1}[K']\{u\} \qquad (5)$$

By formula (4) and (5),

$$c=\frac{1}{2}\{P\}^{T}\{u\}=-\frac{1}{2}\{P\}^{T}[K]^{-1}[K]\{u\}$$
$$=\frac{1}{2}\{u^{i}\}^{T}\left[K^{i}\right]\{u^{i}\} \tag{6}$$

In equation (6), the u^i is the i_th element's displacement vector. So, the definition a_i:

$$a_i=\frac{1}{2}\{u^{i}\}^{T}\left[K^{i}\right]\{u^{i}\} \tag{7}$$

serves as the sensitivity coefficient for the collectivity stiffness constrain problems. The sensitivity coefficient denotes the alteration of the strain energy aroused by the removed i_th element. Actually, a_i is element strain energy, which is easily carried out by using element stiffness matrix and element displacement vector in the element level. It is worthy to point out that c and a_i are all positive value.

In order to avoid the effect on the value of elements's strain energy by the size of elements, density of strain energy D_i was introduced:

$$D_i=\frac{c}{\Delta V_i}=\frac{1}{2}\{u^{i}\}^{T}\left[K^{i}\right]\{u^{i}\}/\Delta V_i \tag{8}$$

Where, ΔV_i is the volume of the i_th element.

Using equation (8) all the density of strain energy D_i is calculated and been ranged as follow:

$$\mathbf{p}=(D_1,D_2,\cdots,D_{NN})^{T} \tag{9}$$

$$\Delta D_i=D_i/\max(D_1,D_2,\cdots,D_{NN}) \tag{10}$$

Where ΔD_i is called as factors with dimension and they are in the range of 0-1.The factors are used to identify the sensitivity value of the car body.

IV. SENSITIVITY ANALYSE OF AUTOBODY STRUCTURE

Applying the stiffness criterion, sensitivity analyse of autobody structure has been done. The flow of sensitivity analyse is shown in Fig.4:

FE analyse

↓

Calculate the elements's strain energy: a_i

↓

Calculate the density of strain energy: ΔD_i

↓

Produce sensitivity vector of the density of strain energy: $\mathbf{p}$

↓

Range the factor of density of strain energy: ΔD_i

↓

The result of sensitivity analyse

Figure 4. The flow of sensitivity analyse

By sensitivity analyse, the main pates of the car body which sensitivity value under bending and torsion load cases are maximal are show in Fig.5 and Fig.6

Figure 5. The parts of maximal sensitivity value of car body under torsion load case

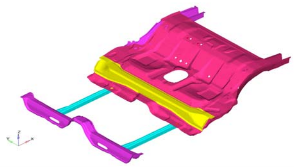

Figure 6. The parts of maximal sensitivity value of car body under bending load casepage

V. OPTIMIZATION DESIGN AND NUMERICAL SIMULATION OF CAR BODY

For the reason that the disperse thickness value of car body parts in design region and the time-consuming for each analyse, the idea that adopt Uniform Design to arrange test is carried out. With the Uniform Design Table, thickness value is selected for the modified car body parts. The Uniform Design method[22] is proposed together by Domestic mathematician Fang Kaitai and Wang Yuan. This method makes the filter factor as aim to process for the better optimization value in step, which will need much less tests. The Uniform Design is one of DOE test designs which makes the tests point disperse evenly in the design region. To need less tests and better representative are its merits, especially when needing more tests. Plentiful and sbustantial production have been acquired in medicine, aviation, chemical engineering, weave industry and military in domestic since the UD method came into being.

TABLE I.
UNIFORM:DESIGN TABLE $U_{13}\left(13^{12}\right)$

No.	1	2	3	4	5	6	7	8	9	10	11	*12*
1	1	2	3	4	5	6	7	8	9	10	11	*12*
2	2	4	6	8	10	12	1	3	5	7	9	*11*
3	3	6	9	12	2	5	8	11	1	4	7	*10*
4	4	8	12	3	7	11	2	6	10	1	5	*9*
5	5	10	2	7	12	4	9	1	6	11	3	*8*
6	6	12	5	11	4	10	3	9	2	8	1	*7*
7	7	1	8	2	9	3	10	4	11	5	12	*6*
8	8	3	11	6	1	9	4	12	7	2	10	*5*
9	9	5	1	10	6	2	11	7	3	12	8	*4*
10	10	7	4	1	11	8	5	2	12	9	6	*3*
11	11	9	7	5	3	1	12	10	8	6	4	*2*
12	12	11	10	9	8	7	6	5	4	3	2	*1*
13	*13*	*13*	*13*	*13*	*13*	*13*	*13*	*13*	*13*	*13*	*13*	*13*

This paper selecte the Uniform Designs Table $U_{13}(13^{12})$ to arrange test. The table $U_{13}(13^{12})$ is showed as Table 1

The possible thickness value of car body parts is outspreaded around the original value as table 2.

TABLE II.
EXAMPLE OF POSSIBLE THICKNESS VALUE

1	2	3	4	5	6	7	8	9	10	11	12	13
0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00	1.05	1.10	1.15	1.20

The optimization result was showed in Fig 7:

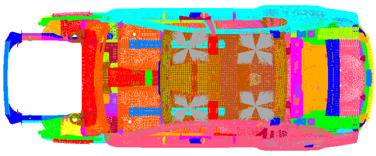

Figure 7. The final structure of the car body

The whole mass of the car body reduced form 301.5Kg to 292.6Kg . The maximum stress reduced form 192MPa to 187MPa under the bending load case and it keeped fixedness under torsion load case.The stiffness sensitivity of the whole structure tends to reasonably after the optimization.

VI. CONCLUSIONS

In this paper, stiffness criterion are applied to calculate the sensitivity of the whole autobody. Based on the result of sensitivity analyse, Uniform Design is used to arrange tests. The shape optimization and size optimization of parts of components are implemented. The mass of the whole car body decrease 8.9Kg and the stiffness of the autobody don't reduce. According to the numerical simulation of the whole car body, the optimization result is satisfaction.

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REFERENCES

[1]. Esping Bjorn JD. The OASIS structural optimization system. Computers and Structures, 1984, 23(3): 365-377

[2]. Braibant V, Fleury C, Shape optimal design using Bsplines. Computers Methods in Applied Mechanics and Engineering,1984,44(3):247-267

[3]. Bennett JA, Botkin ME. Structural shape optimization with geometric desbription and adaptive mesh refinement. AIAA Journal, 1985, 23(3): 458-464

[4]. Botkin ME, Yang RJ, Bennett JA. Shape optimization of three dimensional stamped an solid automotive components, the optimum shape. In: Bennett, Bokin,eds. Automated Structural Design, New York: Plenum Press,1986

[5]. SUI Yun-kang, ZHONG Wan-xie, QIAN Ling-xi. Optimum design of structures composed of bars-membranes-beams program DDDU-2[J]. Journal of Dalian Institute of Technology, 1983, 22(1): 21-36.(in Chinese)

[6]. SUI Yun-kang, WANG Xi-cheng. Structural optimum program system DDDU-2F for complicated engineering practice [J]. Computational Structural Mechanics and Applications, 1985, 2(3): 73-81.(in Chinese)

[7]. Sui Yunkang. Optimum method of discrete variables for the structure composed of multielements and program system DDDU-4. Shanghai Journal of Mechanics, 1987, (4): 12～23 (in Chinese)

[8]. Gu Yuanxian, Cheng Gengdong. Development and applications of computer aided structural design optimization package MCADS. Computational Structural Mechanics and Applications, 1995, 12(3): 304～307 (in Chinese)

[9]. Bendsoe MP, Kikuchi N. Generating optimal topologies in structural design using a homogenization method. Comp Meth Appl Mech Engrg, 1988, 71(1): 197-224

[10]. Rong JH, Xie YM, Yang XY, et al. Topology optimization of structures under dynamic response constriants. Journal of Sound and Vibration,2000,23 4(2):177-189

[11]. Rung JH, Xie YM. Yang XY. An improved method for evolutionary structural optimization against buckling. J Computers& Structures, 2001, 79:253-263

[12]. Rong Jianhua, Jiang Jiesheng, Yan Donghuang, XU Bin. Bridge structure topology optimization with multiple constraints. Engineering Mechanics, 2002,Vol.19 No.4 P.160-165(in Chinese)

[13]. Xie Y M, Steven GP. Evolutionary Structural Optimization London: Springer-VerlagL imited, 1997.

[14]. Kim H,Querin QM, Steven GP, et al. Development of an intelligent cavity creation (ICC)algorithm for evolutionary structural optimization. In: Proceedings of the Australian Conference on Structural Optimization, Sydney, 1998.241-249.

[15]. Rong Jianhua, Zheng Jianlong, Xu Feihong. Structural Dynamic Modification and Optimization Design. Beijing: People's Communication Press, 2002. 10 (in Chinese)

[16]. Ye Yuanlie, Qin Dongchen, Chen Lihua. The structural optimization design of sheet cover. JOURNAL OF MECHANICAL STRENGTH, 1999，21（3）：182－185(in Chinese)

[17]. Gao Yunkai, Lan Xixaoli, Chen Xin. The sensitivity analysis of car body modal modification. Automotive Engineering, 2001, Vol23No.5: 352-355(in Chinese)

[18]. Wang Mingqi, Jin Guodong. The application of Taguchi method in vehicle body skeleton stiffness optimization. Automobile Technology, 1998 No.5: 5-8(in Chinese)

[19]. Lan Fengchong, Chen Jiqing. Optimization and sensitibity analysis of cover panel thickness of loda-supporting autobody, Aeronautical Manufacturing Technology, 005 3： 61-65(in Chinese)

[20]. Qian Lingxi. Engineering structure optimization design.China WaterPower Press, 1983.9(in Chinese)

[21]. Fang Kaitai. Uniform Design and Uniform Designs Table. Science publication.1994.6 (in Chinese)