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Derivation of optimal design of cockpit module considering vibration and heat-resistance characteristics †

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Abstract

Elimination of noise caused by the permanent deformation of interior plastic parts has been one of the major factors driving the design of automotive interior assemblies. Noise, indeed, is one of the main criteria affecting the perception of vehicle quality. Traditionally, noise issues have been identified and rectified through extensive hardware testing. However, to shorten the product development cycle and minimize the amount of costly hardware manufactured, hardware testing must rely on engineering analysis and upfront simulation in the design cycle. In this paper, an analytical study conducted to reduce permanent deformation in a cockpit module is discussed. The analytical investigation utilized a novel and practical methodology, implemented through the software tools ABAQUS and iSight, for the identification and minimization of permanent deformation. Here, the emphasis was placed on evaluating the software for issues relating to the prediction of permanent deformation. The analytical results were compared with the experimental findings for two types of deformation location, and the qualitative correlation was found to be very good. We also developed a methodology for the determination of the optimal guide and mount locations of the cockpit module that minimizes permanent deformation. To this end, the methodology implements and integrates nonlinear finite element analysis with sensitivity-analysis techniques.

Keywords: Key-life test; Cockpit module; Optimal design; Permanent deformation; Differential sound; Sensitivity analysis; Regression function

1. Introduction

Since 1990, the major trend in the development of vehicles designs has been to focus on cost savings and improving functionality by minimizing weight and ensuring safety (i.e., protecting passengers from collision impacts) [1]. However, since weight minimization and safety assurance naturally are con-flicting objectives, a way to solve this problem is to rationally design vehicles for light-materials construction. A reasonable design methodology entails, as the initial step, the develop-ment of an optimal plan by means of computer-assisted struc-tural analysis and modeling. The lightweight materials typi-cally utilized are high-tension steel sheets, plastics, and others [2, 3]. Whereas high-tension steel sheets reduce weight by 5-7%, the result from the use of plastics can be as high as 20% [4, 5]. Hence, developed countries are pursuing the use of plastics in vehicle components as an efficient alternative en-hancing maintainability and fuel economy as fuel prices rise and pollution continues to be a concern. Additionally, the use of plastics enhances design freedom in that they can be formed, by the developed methods, into many and various shapes. The application of plastic parts takes on an even greater importance in domestic markets [6]. However, before the efficiency advantages of plastics can be realized, certain key material requirements (e.g., resistance to road-surface vibration, heat-resistant cycle performance, impact resistance, chemical resistance, etc.) have to be satisfied. The importance of heat resistance and impact resistance is underscored by the keenness of competition among automakers to secure overseas markets.

The modular cockpit shown in Fig. 1 consists almost en-tirely of plastic parts. The annealing phenomenon of mounts which results from irregular vibration- and heat resistance, causes degradation of resistance performance and, resultantly, various sounds. These phenomena give rise, respectively, to serious problems in the functioning of components and dec-rements in the perceived value of products (vehicles). Since the underlying cause is a complex mechanism, it is very

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Fig. 1. Modular assembly of cockpit.

difficult to identify in its basis. Thus, analytical methods isolating such problems need to be applied to improve structural reliability; and further, experimental verification of the feasibility of those methods also is required [7].

However, analysis and optimization technologies with regard to component deformation through complex loads (vibration- and heat resistance) are as yet very poorly developed in the domestic context. In practice, considerable additional expense and time are frequently required to be spent on structural issues that arise during mass production. And he fundamental problems, again, are difficult to solve.

Therefore, the present study, through an analysis of a modular car that is acted upon by a complex load, sought to develop a means of predicting the permanent deformation that arises from vibration and heat. Through the introduction of design-parameter optimization techniques, problems with initial designs could be minimized prior to mass production.

2. The key-life test

In this study, we employed the key-life test of a cockpit module to compare and analyze the quantitative results of tests and analyses. A rough device diagram of the key-life test is shown in Fig. 2. It is very difficult to perfectly describe vibration in accordance with the thermal cycle of the test conditions. Owing to the problems of the time required for analysis and the creep for specific types of material in the steady state, we applied strict constraints in analyzing the problems. We used the values of the three-axis (X, Y, and Z axes) acceleration of the center of the Cockpit Module in the actual test as resonance data. We stipulated the same conditions for the analysis as held for the test. We applied the acceleration value, which was transformed to a load for the sake of analysis, because the resonance data were obtained through an accelerometer [8]. The thermal condition was the same in both cases. Finally, we compared the findings from the analysis and test results by applying elasticity and plasticity data under the strictest condition of 100℃. Though the findings from the analyses and tests will be discussed in the next section, we note here that the region of permanent deformation was found to be in a similar location in the plastic parts. Fig. 3 shows the key-life test device [9].

3. Fundamental experiment

We executed a tension test to obtain data for the elasticity and plasticity regions of PPF 213-59 TY1=SO-5208, PC-ABS MS214-04=NS-5000, and ABS MS225-18 TY5=XR-474, the typical plastic materials used in the industry. This test entailed use of the displacement controller of the electric hydraulic Shimadzu Dynamic Testing System at a rate of 50mm/min under five thermal conditions (-40℃, 23℃, 50℃, 90℃, 100℃). We used a 3-zone-type electric resistance furnace to maintain the high temperatures, and we employed a k-type thermocouple for fine sample-temperature control (within ±1℃ of the test temperature). The test sample was ASTM D638 Type 1, as shown in Fig 4. We determined the average tension value from the test data obtained from five replications of the test [3, 4].

Fig. 5 shows the Stress-Strain Curve of PPF 213-59

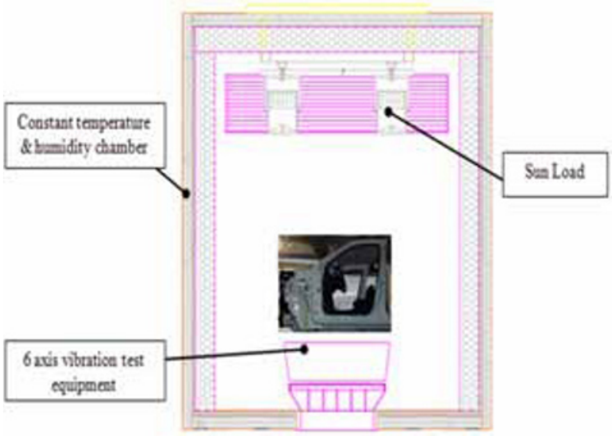


Fig. 2. Key-life test device diagram.

Fig. 3. Key-life test [9].

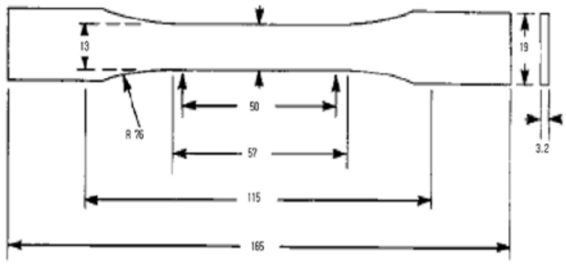


Fig. 4. ASTM D638 Type 1 specimen.

Table 1. Mechanical properties of specimen.

Temperature	Tensile strength (Mpa)	Yield strength (Mpa)	E (Mpa)	Poisson's ratio
-40℃	52.4	43.8	7,060	0.34
23℃	32.5	20.3	3,574	0.44
50℃	26.9	15.5	2,174	0.47
90℃	19.2	11.4	1,413	0.52
100℃	15.9	9.8	1,216	0.54

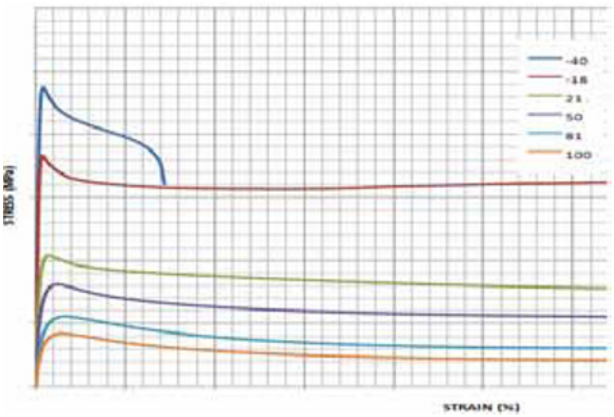


Fig. 5. Results of tension test at each temperature.

TY1=SO-5208, which is used mostly in the cockpit module for the temperature constraint. Table 1 lists the data on the mechanical properties of the material.

4. Finite element analysis

We performed an analysis of the cockpit module as a preliminary study in the development of a process for reducing permanent deformation. Through a qualitative comparison, we confirmed the adequacy of our analytical procedure.

4.1 Finite element model

This section describes the constitution of the finite element model used for the cockpit module. The finite element model of the cockpit module (Fig. 6) comprises 55 sub-components similar to those of the real module. As mentioned earlier, the materials used are four types of plastic (PPF, PC-ABS, ABS, TPO) and five types of steel material (SPHC, SPCC, STK500, SPFC590, SECC).

We assumed the boundary conditions used in the analysis to be the main mounts jointing the chassis to the body. These conditions were fixed for rotary and translational motion. The four mounts of the upper part and the center-guide part were fixed except for X translation and rotation, as depicted in Fig 7. We assigned the load conditions as the numerical values of gravity type to the overall model, as clarified in Fig. 8. The gravity values were acquired from the resonance data obtained in the key-life test. We calculated the numerical value of the gravity by means of the acquired value of the acceleration and

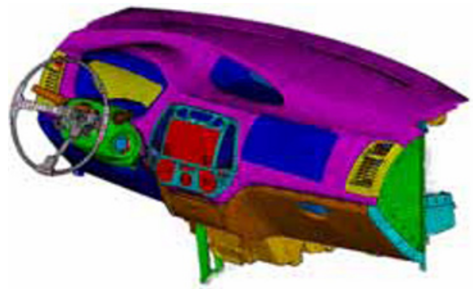


Fig. 6. Finite-element model of cockpit module.

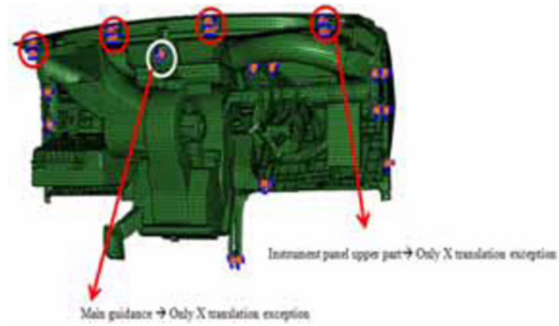


Fig. 7. Boundary conditions.

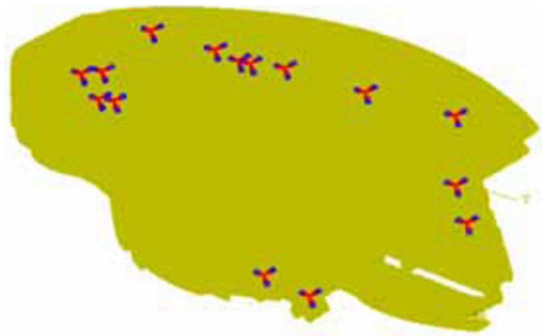


Fig. 8. Load conditions.

the weight of the overall model.

4.2 Finite element analysis

Fig. 9 illustrates the results of the analysis. Fig. 10 indicates the permanent deformation of the overall model. With high temperatures, stress and permanent deformation increase. The extent of permanent deformation was approximately 2.54. The program used in the analysis was ABAQUS Ver. 6.5 [10], a commercial finite element analysis application.

Fig. 11 shows the results of the key-life test. We found that deformation was effected in the part adjacent to the audio box and the side cover. The audio box was made of the plastic material PC-ABS, and the side cover, of PPF. The purpose of the key-life test was to determine the gap opened by permanent deformation of parts. The test helped us to deduce the optimal design through design alterations effected by heat and vibration. We found the results of the finite element analysis to be similar to those of the key-life test. Therefore, it

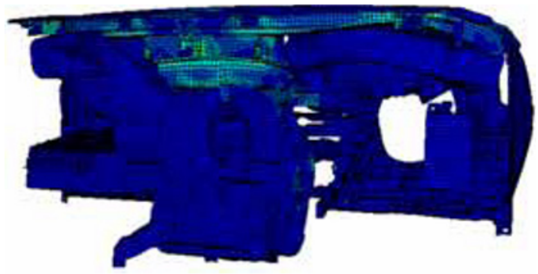


Fig. 9. Result of analysis (stress contour).

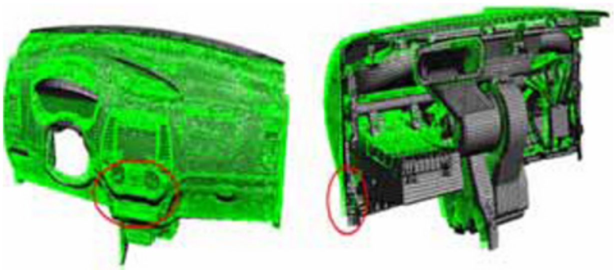


Fig. 10. Result of analysis (permanent deformation).

Fig. 11. Result of key-life test (permanent deformation).

made sense for us to continue the analytic process. We concluded that permanent deformation results in various types of sound.

5. Optimization of positions of guides

As already mentioned, we concluded that the deformation that was produced in the part adjacent to the audio box and the side cover resulted from the concentration of the stress on the upper guide of the cockpit module. This phenomenon leads to deformation of the overall model. In this section therefore, we describe, according to the results of the finite element analysis and key-life test, the optimal design that reduces the permanent deformation of plastic parts adjacent to other deformed plastic parts. Eq. (1) specifies the optimization formulation.

$$\begin{aligned}&\textit{Find}\ \ A, B, C, D\ \textit{Guide's Location}\\&(\textit{Crossways of Cockpit}\ \text{module})\\&\textit{to}\ \min\textit{imize}\\&\textit{Maximum Stress} + \textit{Guide Stress}\ \ (4\,\textit{Guide})\end{aligned}$$

Table 2. Factors and levels.

Factor	Level 1	Level 2	Level 3
A	-5	0	5
B	-15	0	15
C	-15	0	15
D	-5	0	5

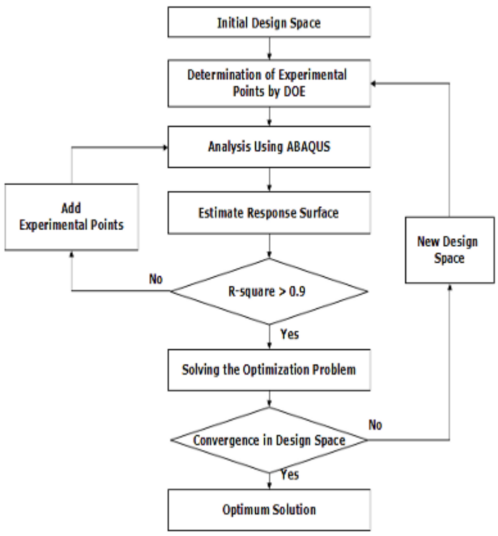


Fig. 12. Flowchart of methodology for optimal design of mount positions.

$$\begin{aligned}&\textit{Subject to}\\&-5mm \le A \le 5mm\\&-15mm \le B \le 15mm\\&-15mm \le C \le 15mm\\&-5mm \le D \le 5mm\end{aligned} \tag{1}$$

Fig. 12 illustrates the process for guide-position optimization. proposed in this study. In light of the phenomenon of the concentration of stress in the part adjacent to the guides, the design variables were the positions of the four mounts. As shown in Fig. 9, the main factor is the positions of the guides. We assigned a stress level to each factor, as in Eq. (1). The objective function is the sum of the stress of the part of interest and the maximum stress of the overall model. We performed a DOE (Design of Experiment) that was applied to the full factorial design for three levels of four factors, as shown in Table 2. Table 3 describes the part of interest and the maximum stress of the overall model, as deduced by the analysis.

The second-order regression function assumed the form shown in Eq. (2); the R-squared value was 0.927, which is close to 1. This means that the response surface was equal to the actual response quantity; hence, we concluded that the deduced second-order regression function was appropriate.

$$\begin{aligned}y=&270.887142857143+0.219285714285719X_1+0.0616984126984126X_2\\&+0.579841269841269X_3+0.0921587301587295X_1X_2\\&-0.0810793650793653X_1X_3+0.390076190476191X_1X_4\\&+0.00718306878306879X_2X_3+0.0725460317460317 46031X_2X_4\\&0.135571428571429X_1^2+0.0363841269841 27X_2^2\\&-0.00640423280423263X_3^2-0.270790476190476X_4^2\end{aligned} \tag{2}$$

Table 3. Orthogonal array [44L15] table and results.

NO.	A	B	C	D	MAX. (MPa)	GUIDE (MPa)	SUM (MPa)
1	1	1	1	1	249.6	35.49	285.09
2	1	2	2	2	245.3	27.88	273.18
3	1	3	3	3	252.3	23.34	275.64
4	1	1	3	3	247.7	25.19	272.89
5	1	2	1	1	241.9	21.96	263.86
6	2	1	2	3	241.7	20.32	262.02
7	2	2	3	1	252.9	23.00	275.90
8	2	3	1	2	246.6	21.34	267.94
9	2	1	1	2	244.3	25.63	269.93
10	2	3	3	1	249.8	30.17	279.97
11	3	1	3	2	250.6	25.29	275.89
12	3	2	1	1	245.2	25.18	270.38
13	3	3	2	3	251.6	22.36	273.96
14	3	1	2	1	246.0	21.95	267.95
15	3	2	3	2	252.3	23.64	275.94

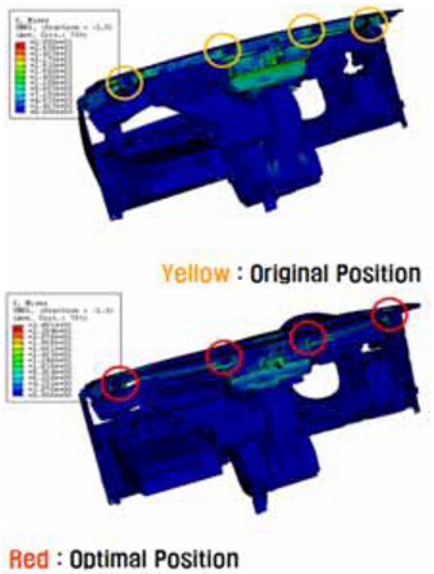


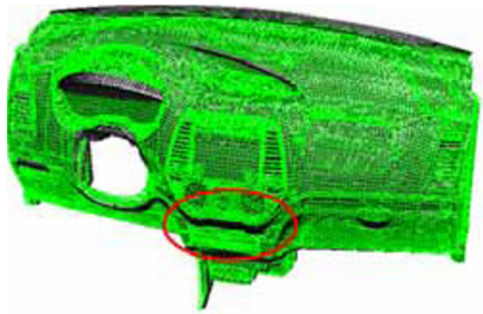
Fig. 13. Results of optimization (stress contour).

Owing to the fact that the regression equation in Eq. (2) is a simple mathematical model, it was easy to deduce the optimal values: A = -4.713mm; B = 1.980mm; C = -14.217mm; D = 4.892mm.

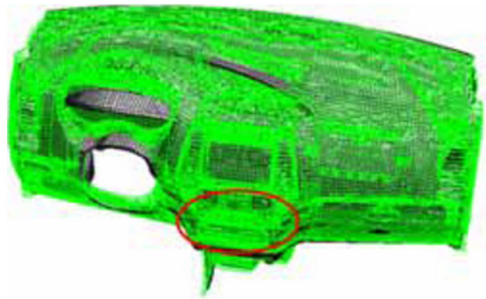
Table 4 lists the results of a comparison between the response quantities of the regression function and the values deduced from the analysis. The numbers within parentheses indicate the extent to which deformation has reduced in comparison with the initial model. The percentage error in the comparison between the response quantities of the regression function and the values deduced from the analysis is 2.3%, which is permissible. Fig. 13 shows the stress contour in the analysis result. Fig. 14 shows the permanent deformation of the cockpit module.

Table 4. Results of analysis.

	Original Model	Regression model	Result of analysis
GUIDE stress	28.12	25. 36 (-9.82%)	24.91 (-11.42 %)
Maximum stress	267.20	241.02 (-9.78 %)	242.50 (-9.24 %)
Guide stress + maximum stress	295.32	266.38 (-9.79 %)	267.41 (-9.45 %)
Plastic strain	2.545	-	1.640 (-35.6%)



(a) Initial model



(b) Optimal model

Fig. 14. Result of optimization (permanent deformation).

6. Conclusions

In this study, with reference to the cockpit module of a car, we developed and applied a process for deriving an optimal design that minimizes permanent deformation. The design process was obtained through tests of and analytical research into permanent-deformation prediction for the cockpit module. Finally, we developed a program that supports cockpit module design. The overall results obtained and conclusions drawn are as follows.

We determined that permanent deformation is a primary cause of the irregular occurrence of various sounds.

We traced the direction of vulnerability in the cockpit module by understanding the specific characteristics of the six mounts used in it. Then, by qualitatively comparing the results of a finite element analysis with those of a key-life test, we obtained the regions of occurrence of the finite, permanent deformation, which regions were found to surround the mounts. Subsequently, we determined a causal mechanism for the occurrence of the permanent deformation.

In summation, through key-life tests and analysis, we theorized a process of optimal cockpit module design that minimizes permanent deformation.

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