

# THICKNESS OPTIMIZATION OF AN AUTOMOBILE BODY FOR NATURAL FREQUENCY MAXIMIZATION

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## Abstract

The paper presents design optimization of an automobile body for dynamic stiffness improvement. The thicknesses of plates making-up the monocoque body of an automobile were employed as design variables for optimization and the objective was to increase the first torsional and bending natural frequencies. By allotting one design variable to each plate of the body, compared to previous works based on element-wise design variables, design space of optimization was reduced to a large extent and numerical instabilities such as checkerboard pattern was efficiently evaded. The method resulted to a considerable amount of increase in the automobile body's torsional and bending natural frequencies. Considering manufacturability of the optimized result, the converged values of plate thicknesses were approximated to commercially-available values by appropriately reflecting their design sensitivities.

## INTRODUCTION

Global market for the automobile industry has made manufacturers produced cost-effective, state-of-the-art competitive models to meet the ever-increasing demands. To this end, CAE-based structural optimization techniques have been actively utilized to design light-weight auto parts with high static and dynamic performances. To mention a few, optimization was used for weight reduction of a sub-frame in suspension system [1], to determine fuel tank shape and location of weld points [2, 3]. Other applications are the design of a rear-view mirror with enhanced dynamic performance [4] and improving the fatigue life of a lower control arm [5].

In this paper, we present the application of CAE-based optimization method for increasing overall dynamic performance of an automobile body. The thicknesses of plates making-up the monocoque body of an automobile are parameterized with design variables for optimization. The design objective is to maximize the first torsional and bending natural frequencies. Optimization is performed on the model of an already-produced car. The thicknesses of the plates are varied with respect to the design variables, so that optimization algorithm will reinforce the plates which have great influence on the increase of frequencies.

The optimization of a full car model for dynamic performance increase had

been performed where the BIW (body-in-white) model of Porsche 928 was discretized with over 34,000 finite elements [6]. However, the design space in the approach was huge with many design variables and consequently, numerically costly. Furthermore, the results of thickness optimization are prone to having checkerboard patterns caused by numerical instabilities of finite elements [7]. Because the optimization method used continuous design variables, the optimized thicknesses were not discretely calculated, the optimized body becomes unfavorable for production.

The proposed optimization in this work is formulated within the following framework. 1) The design variables are allotted to each plate component of a monocoque body, and thus the number of design variables and design space can be significantly reduced compared to the approach in [6]. 2) Because the elements on the same plate share one common design variable, numerical instability such as checkerboard pattern will be evaded without introducing any filters [8]. 3) Optimization is based on continuous variable space. Hence, gradient-based fast optimization algorithms are employed as the optimizer. Since commercially-available plate thicknesses for the automobile body are discrete, optimized thicknesses must be approximated to the discrete values to ensure manufacturability. 4) We propose efficient thickness approximation approach which minimizes performance deterioration of the optimized body. By considering design sensitivities of the optimized model, the post-processed model with discrete thicknesses can have almost similar stiffness and mass compared to the initially optimized model. To discretely optimize the plate thicknesses, non-gradient-based algorithms such as the genetic algorithm [9] or the particle swarm method [10] might be introduced. However, computational cost for such optimizations will be enormous especially for full car model as in this work. The commercial software ANSYS [11] with its APDL (ANSYS Parametric Design Language) feature and DOT [12] are used for the finite element analysis and optimization, respectively.

## THICKNESS OPTIMIZATION PROBLEM

The BIW model of a 251.4-kg car which is used for optimization in this work is illustrated in Fig. 1(a). The model consists of 51 steel plate parts 19 of which in the middle rear region of the car are set as design variables as shown in Fig. 1(b).

The optimization for increasing torsional and bending frequencies of the BIW model is formulated as

$$\text{Maximize: } F_{\rho \in N} = w \frac{f_T(\rho)}{f_T^0} + (1-w) \frac{f_B(\rho)}{f_B^0} \quad (1a)$$

$$\text{Subject to: } G = \sum_{i=1}^N m_i - M_0 < 0 \quad (1b)$$

$$0 \leq \rho_i \leq 1 \quad (i = 1, 2, 3, \dots, N), \quad (1c)$$

where  $f_T$  and  $f_B$  are the first torsional and bending frequencies, respectively while the superscript 0 indicates the values calculated from the initial model.  $\rho \in N$  denotes the design variable vector, which is parameterized with plate thickness. The contribution of each frequency to the objective is controlled by adjusting the weighting factor,  $w$  ( $0 \leq w \leq 1$ ). The design constraint in (1b) is imposed on total mass of the model not to exceed the prescribed mass  $M_0$ , and  $m_i$  in (1b) signifies the mass of the plate which is related to  $\rho_i$ .

The parameterization of the design variable with the plate thickness is defined as

$$t_i = (\alpha + \beta \cdot \rho_i) t_i^0 \quad i = 1, 2, 3, \dots, N \quad (2)$$

where  $t_i^0$  is the thickness of the plate  $i$  of the original model,  $\alpha$  and  $\beta$  are parameters to express the maximum and minimum plate thickness for optimization, respectively. In this work, the parameters are set as  $\alpha = 0.8$  and  $\beta = 1.2$ , so plate thicknesses are varied 80-200% according to the values of their design variables.

With the model's initial configuration, the first torsional mode is found to be the 8th mode with its natural frequency 22.7Hz and the first bending mode and its natural frequency is the 11th mode and 33.5Hz, respectively as described in Fig 2.

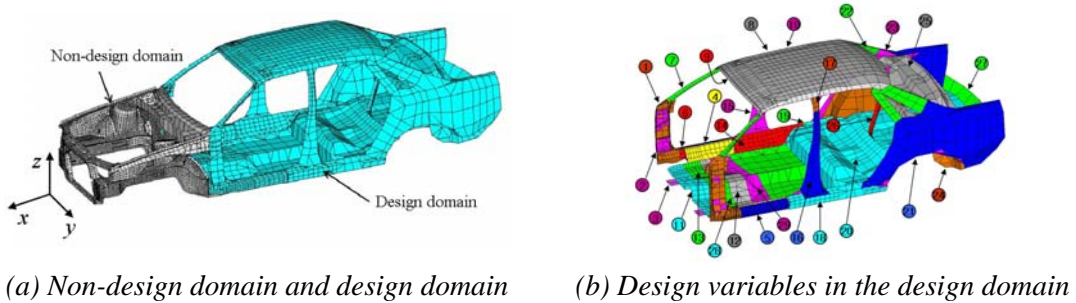


Figure 1 – Body-in-white model of an automobile

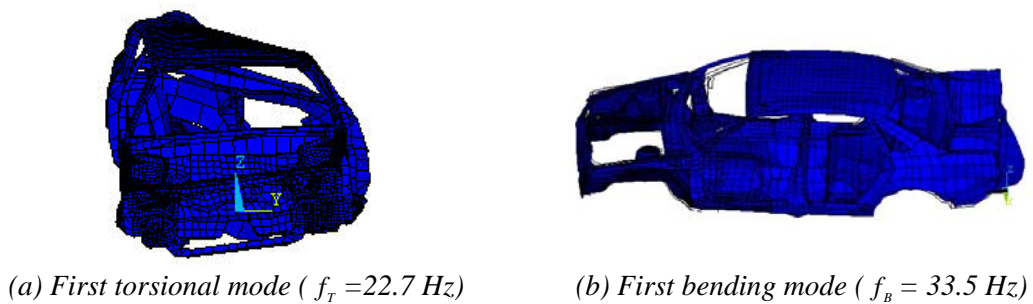


Figure 2 – Modal analysis of the model in Fig. 1 using ANSYS shell 63 element

## OPTIMIZATION RESULTS AND DISCUSSION

### Maximization of the torsional and bending natural frequencies

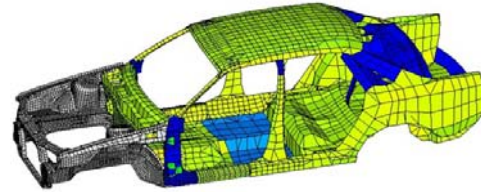
During optimization there exists high possibility of mode sequence change due to structural configuration changes at each iteration step. Therefore the mode of interest should be tracked during the process. We used the MAC-based mode-tracking method. The MAC (modal assurance criteria) between two different modes is defined as [10]

$$\text{MAC}(\Phi_A, \Phi_B) = \frac{|\Phi_A, \Phi_B|^2}{(\Phi_A^T \Phi_A)(\Phi_B^T \Phi_B)} \quad (3)$$

where  $\Phi_A$  and  $\Phi_B$  denote modal shape vectors of mode A and B, respectively. The MAC value is obtained as  $0 \leq \text{MAC} \leq 1$ . If  $\text{MAC} = 1$ , it indicates that the two mode shapes are exactly the same with each other.

*Table 1 Frequency increase results by multi objective topology optimization with 1% mass increase ( $w = 0.5$ )*

	Initial design [Hz]	Optimized design [Hz]	Frequency increase
Torsional frequency	22.7	28.4	5.7
Bending frequency	33.5	39.2	5.7



*Figure 3 – Thickness optimization result by multi-objective optimization with 1% added mass (■  $0.8 < \rho_i \leq 1$ , ■  $0.6 < \rho_i \leq 0.8$ , ■  $0.4 < \rho_i \leq 0.6$ , ■  $0.2 < \rho_i \leq 0.4$  and ■  $0 < \rho_i \leq 0.2$ )*

Taking  $w = 0.5$  and 1% mass-increase-constraint condition in (1), optimization results are listed in Table 1. As can be observed, there is a frequency increase and thus high dynamic stiffness for the optimized body can be obtained compared to the original model. Note that mode sequence has changed; from 8<sup>th</sup> to 10<sup>th</sup> for the first torsional mode and from 11<sup>th</sup> to 13<sup>th</sup> for first bending mode. Fig. 3 illustrates the optimized plate thicknesses.

### POST-PROCESS FOR THICKNESS DISCRETIZATION

The plate thicknesses are optimized based on continuous design variables  $\rho_i$ , so their values after optimization are also continuous. However, manufacturing all the plates having these thickness dimensions is rather impractical. In this work, the manufacturability issue of optimization is considered by approximating optimized

plate thicknesses to the following discrete values in [mm].

$$\bar{t}_i \in \left\{ 0.6, 0.65, 0.7, 0.8, 0.9, 1.0, 1.2, \right. \\ \left. 1.4, 1.6, 1.8, 2.0, 2.3, 2.6, 3.0 \right\} [\text{mm}] \quad (4)$$

To approximate the optimized thicknesses to the discrete values we consider design sensitivities of the optimized result, from which we can obtain far better approximated model than using a simple round-down/off approach. Accordingly, for the design variables with objective sensitivity less than zero, the corresponding optimized thicknesses,  $t_i^{opt}$  should be approximated to their nearest smaller discrete thicknesses,  $\bar{t}_i$  in (4) to reduce total mass of the automobile body. Conversely, if a design variable has positive objective sensitivity, its discrete thickness is given using the round-off-based approach. The proposed approach is summarized as

$$\text{If } \frac{\partial F}{\partial \rho_i} \leq 0 \rightarrow \text{approximate to the nearest smaller thickness in (4),} \quad (6a)$$

$$\text{else if } \frac{\partial F}{\partial \rho_i} > 0 \rightarrow \text{approximate to the nearest thickness in (4).} \quad (6b)$$

Using (6), we approximate the optimized thicknesses in Fig. 3 to the discrete values, by which the natural frequencies of the post-processed model are recalculated and listed in the rightmost column of Table 2. Though there is small decrease in frequencies, the final mass of the automobile body is smaller than that of the model before the post-process, which shows the efficiency of the proposed thickness discretization approach. The final thicknesses  $\bar{t}_i$  are listed in Table 3.

*Table 2 – Performances of the post-processed model for torsional and bending frequency maximization problem with 1% added mass*

	Initial	Optimized result	Post-processed results (final)
Mass [kg]	251.4	254.0	251.5
Torsional freq. [Hz]	22.7	28.4	28.2
Bending freq. [Hz]	33.5	39.2	39.1

*Table 3 – Optimized thicknesses  $t_i^{opt}$  and their post-processed thicknesses  $\bar{t}_i$  for torsional and bending frequency maximization problem with 1% added mass*

$i$	$t_i^0$	$t_i^{opt}$	$\bar{t}_i$	$i$	$t_i^0$	$t_i^{opt}$	$\bar{t}_i$
1	1.0	1.9860	2.0	16	1.4	1.1228	1.2
2	1.8	1.9350	2.0	17	1.0	1.9868	2.0
3	0.8	0.6416	0.65	18	1.0	0.8020	0.8
4	1.4	1.1228	1.2	19	1.4	1.1228	1.2
5	1.0	0.8020	0.8	20	1.2	1.0959	1.0
6	1.4	1.1228	1.2	21	1.0	0.8020	0.8
7	3.0	2.4060	2.3	22	1.0	1.6706	1.6
8	2.0	1.6040	1.6	23	1.0	0.8020	0.8
9	1.4	2.7814	2.6	24	1.0	0.8239	0.8
10	1.0	1.4485	1.4	25	1.0	1.9900	2.0
11	1.6	1.2832	1.2	26	1.0	1.9898	2.0
12	1.4	1.1228	1.2	27	1.6	3.1708	3.0
13	1.4	2.1942	2.3	28	1.0	0.8020	0.8
14	1.4	1.1228	1.2	29	1.2	0.9624	1.0
15	1.6	1.2832	1.2				

## CONCLUSIONS

Torsional and bending frequency maximization problem for the BIW model of an automobile body was presented in this work. Compared to the existing element-wise design variable approach, by allotting design variables onto each plate of the model and linearly parameterizing the design variable with its corresponding plate thickness, the size of the design space for optimization could be significantly reduced. After optimization, optimized plate thicknesses were discretized to the nearest available thicknesses for increasing manufacturability. To minimally deteriorate the optimized performances after discretization, design sensitivities of the objective were considered and the mass increase after thickness approximation could be efficiently suppressed.

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