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Lightweight Optimization of Headrest Modules Including Flat-Plate Sliding Brackets

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Abstract
The rear-folding-type seat may collide and cause seat damage due to interaction with the front seat when the drawn-out headrest is folded. This study investigated the mechanism of a folding-type seat that keeps the headrest free from interference with the front seat when the rear seat is being folded, as well as a method for weight reduction of automobile parts. In this paper, the seat back interlocking mechanism is also presented. The no occurrence of interference was verified via trajectory analysis. Furthermore, this study proposes a module design for the proposed mechanism, and finite element analysis (FEA) was conducted to verify that the proposed structure satisfies the static strength requirements in compliance with the relevant regulations. Furthermore, the design of experiments (DOE) method was used to propose a weight-reduction method for the designed automotive components and its feasibility was verified.

Keywords: Headrest, Optimization, Design of experiment, Lightweight, Seat

INTRODUCTION

With the popularization of leisure and cultural activities, there has been a rise in the demand for an increased vehicle cargo space. Ex tending vehicle space by folding the rear seats has been commonl y used to meet this demand. At the same time, increased safety aw areness in recent times has contributed to strengthening the releva nt regulations by mandating the installation of rear seat headrests i n automobiles. Headrests are designed to be adjustable in height c onsidering the user's body size. The headrest of a drawn-out rear seat interferes with the front seat while the seatback is folded, whi ch, in turn, requires front seat repositioning and headrest length ad justment. To solve this problem, a new mechanism is required tha t would avoid front seat interference while folding the seatback of the rear seat. Choi et al. [1] emphasized the importance of headrest s drawn out to the proper height. Kim [2] employed mathematical modeling to design the mechanism, which demonstrates kinemati c motion by using slots and links for trajectory control. Yang [3] d esigned an operating mechanism via trajectory analysis.

Automotive lightweight is a popular approach to improve the fuel economy and simultaneously deal with environmental issues. Wit h the development of luxury and intelligent vehicles, such an appr oach can be used to offset the impacts of weight increase due to a rising number of in-vehicle components to enhance safety, conve nience, and affective value. With an increase in the number of co mponents added to existing vehicles for new features, the sub sequent growth in the vehicle's total weight is unavoidable, which calls for ae lightweight analysis with the objective of minimizing the total vehicle weight. Most commonly used m ethods of in-vehicle component weight reduction include mat erial change [4], [5] and topology optimization [6] based on com puter programs. However, in case of brackets, which are the s ubjects of lightweight in this study, topology optimization is not suitable, as the brackets have a relatively small thickness compared to its length or width. Design of experiments (DOE) can be also utilized for lightweight. For instance, Choi [7] im plemented a DOE-based size optimization design approach, while M. Hatami [8] utilized DOE to optimize the partial shap e of a variable turbocharger by means of multiple preset para meters and verified the effectiveness of the method.

This paper proposes a new approach for avoiding front-seat i nterference when folding the seatback of the rear seat. The pr esent method utilizes slots and wires to prevent front-seat inte rference by positioning the headrest near the center of rotatio n of the rotating seatback. In this study, the structural design was conducted via trajectory analysis of the headrest, based o n the slot shape, interference avoidance method, and case-stu dy analysis of different seat structures necessary when imple menting the mechanism. 3D seatback modelling was perform ed, which included mechanism design, coupled with FEA usi ng loading conditions suggested by the U.S. Federal Motor V ehicle Safety Standard FMVSS 202a Vertical Test, in order t o evaluate structural safety of the seatback. Based on the anal ysis, bracket weight reduction was achieved in the form of a l ightweight exercise for vehicle components by identifying ex cessively heavy auto parts and minimizing the weight gain. T o that end, this study utilized DOE and analyzed the relations hips between each design variable and the corresponding resp onse variable to present a novel method of lightweight.

STRUCTURAL DESIGN OF SEATBACK INTERLOCKING HEADREST

Mechanism design

Seatback must be folded without colliding with the front seat and with no additional adjustments in the headrest height. Po ssible causes of such problems include the position and postu re of the front seat as well as the height of rear-seat headrest when drawn out. The main purpose of mechanism design in t his study was to eliminate additional manipulations in pursuit of improved convenience, which requires an approach that all

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ows the drawn-out headrest to be adjusted in height as the seatbac k rotates in accordance with a mechanism involving only the rear seats regardless of front seats.

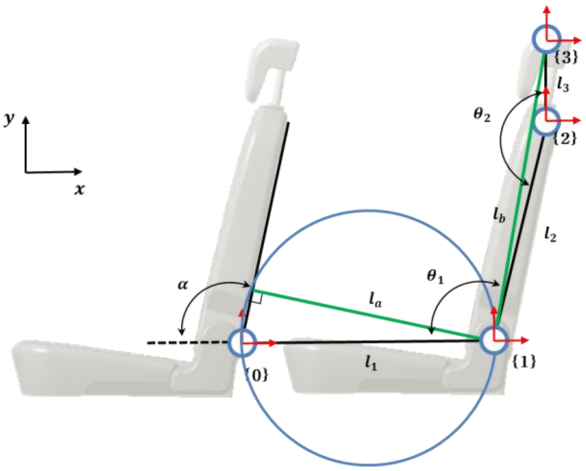


Figure. 1 Avoidance for folding mechanism

Table 1 Design Parameter

Symbol	Description	Symbol	Description
{0}	Coordinate system $\{X_0Y_0\}$	α	The initial angle of front seat
{1}	Coordinate system $\{X_1Y_1\}$	l_a	Minimum distance from {1} to front seat
{2}	Coordinate system $\{X_4Y_4\}$	l_b	straight distance from {1} to {5}
{3}	Coordinate system $\{X_5Y_5\}$	l_1	{0}~{1} distance
θ_1	Seat back angle	l_2	{1}~{2} distance
θ_2	The angle of between $l_4$and l_5	l_3	{3}~{3} distance

Parameter values indicating the total rotation of the seatback an d the front-seat posture, denoted by α and l_1, respectively, were d etermined based on actual vehicle measurements of existing seat. When the rear-seat headrest is adjusted in height with the front se at being fixed in position and posture, the total height of rear seat, l_t should be smaller than $l_a = \sin(180^\circ - \alpha) l_1$ to avoid a colli sion.

$$l_b \fallingdotseq l_2 + l_3 \qquad (1)$$

$$l_a > l_t$$

$$l_1 \sin(180^\circ - \alpha) > l_2 + l_3 \qquad (2)$$

The interlocking headrest mechanism consists of an existing se at structure and an additional movable module and a lever designe d to shift the headrest height-adjustment structure, including head rest and pole bar guide, to where the recliner–lever and lever–hea drest movable modules are connected by wires. Fig. 2 shows a sc hematic of the seatback-interlocking headrest.

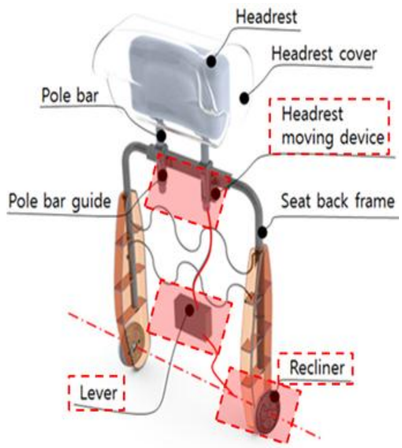


Figure. 2 The seatback folding mechanism

This study presents a mechanism with slots, which allow f or movement with seatback rotation while maintaining the ex isting headrest height. The mechanism includes a moving pat h guide slot and adds a bracket of a certain size to protect inte rnal components and secure the workspace. The size of the br acket is determined based on the workspace available for hea drest components and the moving path slot, bracket fixing, wi dth of headrest, length of the pole bar, and size and thickness of the seat. The shape of the bracket is illustrated in Fig. 3, an d the factors affecting bracket design are summarized in Tabl e 2.

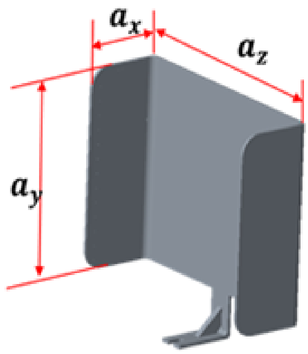


Figure. 3 Shape of bracket

Table 2 Design parameter of bracket

Symbols	Design parameters
a_x	• slot size • work space • fixing area • thickness of seatback
a_y	• slot size • length of bar
a_z	• width of headrest

	• seat size

The headrest must normally be in a 'stationary' state and become 'movable' when the seatback is folded. A linearly designed slot requires a separate fixing device. Furthermore, the headrest should be easily movable when the pulling force is applied to the wire rather than the headrest itself. The start and end positions of the slot were arranged to be inclined, with the distance between the two points set to be 50 mm or greater. Two upper and lower slots at both ends to prevent possible torsion, are arranged to prevent the headrest from rotating.

The wire-driven mechanism, presented in this paper, was designed to allow the headrest to rotate by up to 110° depending on the slot shape. It is assumed that the tip end of headrest moves in the recliner direction, and the wire is a rigid body without deformation in the length direction. To avoid collision with the front seat, the trajectory of the headrest tip is modified by changing the slot shape. The trajectory from the initial position of the headrest tip to the final folded position is also examined in this paper. As shown in Fig. 5, by changing the trajectory, the initial rate of travel can be increased. The slot shapes are designed as shown in Fig. 4, and the trajectory of the headrest tip for different slot shapes is illustrated in Fig. 5.

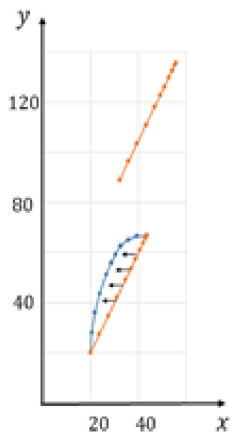


Figure. 4 Trajectory of slot

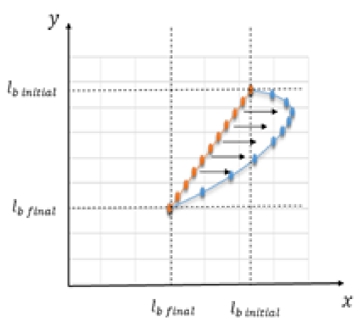


Figure. 5 Trajectory of coordinate system{3}

Trajectory analysis of seatback interlocking headrest

To evaluate interference avoidance using the headrest-interlocking mechanism, a trajectory analysis was performed. As shown in Fig. 1, the coordinates were set for the main areas of the mechanism, proposed in this study, for analysis of the headrest tip trajectory, and the trajectory coordinate systems {2} and {3} were obtained when the seatback was folded to evaluate its interference avoidance with the front seat. The trajectory of the headrest tip while folding a seatback, which varies with differently designed slot shapes, was evaluated with input values of parameters, such as rear-seat space, front-seat posture, and rear-seat size.

The trajectory of the headrest tip was investigated while increasing the seatback rotation angle θ_1 to up to 110°. With increased θ_1, the recliner pulls a wire as the seatback rotates, which shifts the movable module in the axial direction through a lever. The trajectory of the headrest tip is determined based on the slot shape in the coordinate system {2}. The trajectory coordinate systems {2}, {3} are illustrated in Fig. 2.16.

Therefore, it is concluded that the difference in shape between the two slots causes a change in the headrest angle, and the headrest tip moves backwards at an initial stage, all of which contribute to interference avoidance. No collision between the headrest and front seat was observed in this study.

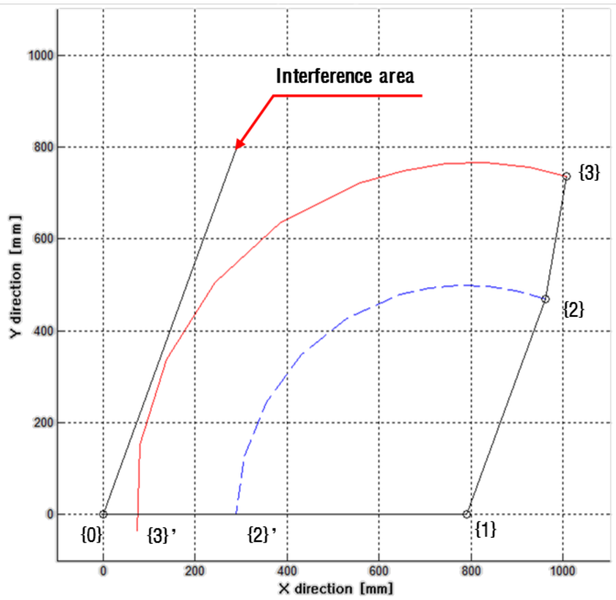


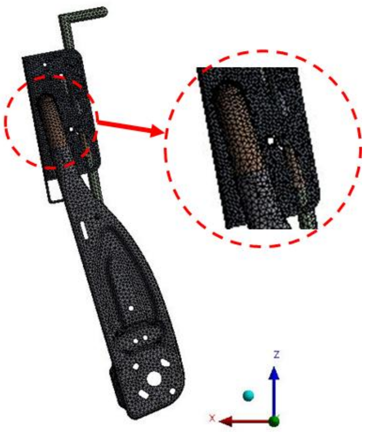
Figure. 6 Trajectory analysis of the folding mechanism

FINITE ELEMENT ANALYSIS

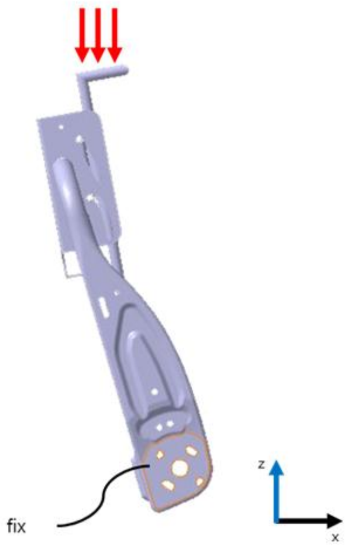
According to the headrest height requirements in the FMVSS 202a, a test for maintaining height must be performed as a mandatory exercise for adjustable headrests with a lock system, and the headrest must be designed to sustain a deformation not exceeding 13 mm from a reference point when a load of 500 N is applied [9]

3D shape modeling was conducted for seatback frames, including the seatback-interlocking headrest mechanism. All parts were made of structural steel. The areas that have no influence on the results were excluded, and all degrees of freedom (DOF) were constrained in the recliner area connecting to the seat cushions. A load, which was gradually increased to 500 N in the vertical direction, was applied at the uppermost point in the headrest for analysis. The maximum load of 500 N was applied for five seconds to evaluate the stress distribution and deformation. Fig. 7 shows the analysis conditions, where (a) illustrates the mesh shape of the model analyzed and (b) illustrates load directions and the DOF constraint conditions. Table 3 summarizes details of analysis model.

Fig. 8 and 9 show FEA results for the seat frames in accordance with the headrest height requirements in the FMVSS 202a. The maximum stress, which appeared to be concentrated at the contact between the bracket and under bar, was 193.28 MPa. Local plastic deformation may have occurred, but at the same time, it can be predicted that no damage will occur. The maximum deformation observed was 2.028 mm, which was smaller than the threshold deformation (13 mm) suggested by FMVSS 202a. Taking the safety factor into consideration, the maximum deformation was 4.33 mm.



(a) Shape of mesh



(b) Boundary condition of analysis

Figure. 7 Mesh and force condition

Table 3 Model data and input force

Name		Values	
		Bracket	Others
Mesh	Nodes	81,999	185,347
	Elements	42,082	80,558
	Size [mm]	3	5
	Type	tetrahedral	
Load [N]		500	

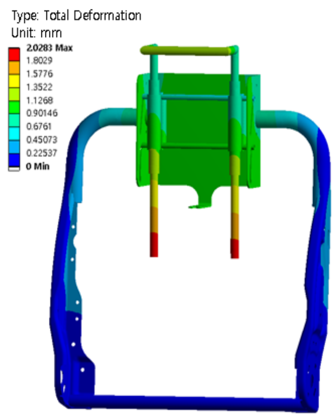


Figure. 8 Deformation of static analysis

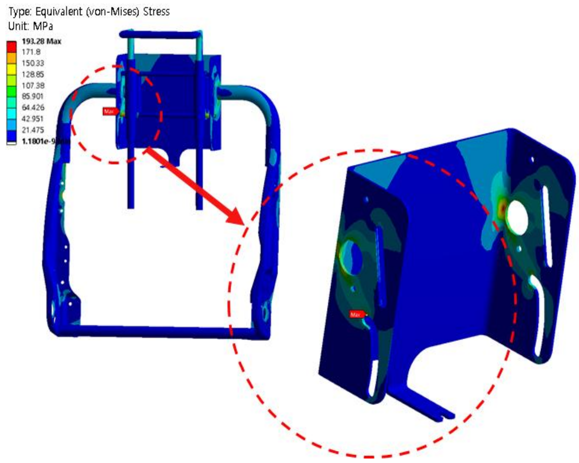


Figure. 9 Stress of static analysis

LIGHTWEIGHT OPTIMIZATION

General full factorial method

The full factorial design, which is a DOE applicable across all combinations at different factor levels, allows an analysis of effects of interaction and main effects and is suitable for determining the characteristics of factors or the optimal combinations.[10], [11]

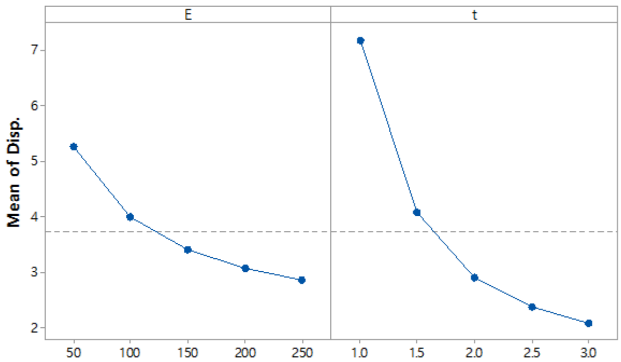
To analyze the effects of design factors, the thickness (t) of brackets was set together with the Young's modulus of elasticity (E) affecting deformation as the physical properties of the materials used in this study. The two-factor five-level full factorial design was used for the simulation conducted 25 times to reduce the weight of bracket. Table 4 lists the values for each f actor level.

Table 4 Design variables and values at each level

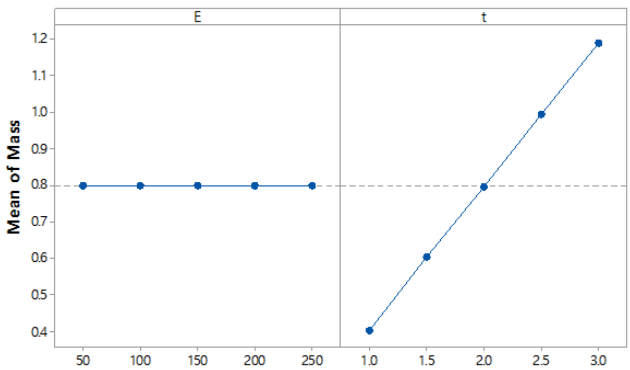
parameter	level				
	1	2	3	4	5
Bracket thickness t [mm]	1	1.5	2	2.5	3
Young's modulus E [GPa]	50	100	150	200	250

Results and analysis

A statistical software (Minitab) was used to analyze the relationship between design variables, seat deformation, and bracket weight. Fig. 10 shows the main effect of each of these factors, and deformation, in particular, is largely affected by thickness as compared to other factors. Young's modulus, also one of the factors, is a physical property only affecting the strength and has no effect on the weight. Fig. 11 shows the results of interaction analysis, and there is no observed interaction, which indicates that the two factors are independent.



(a) Deformation



(b) Mass

Figure. 10 Main effect plot

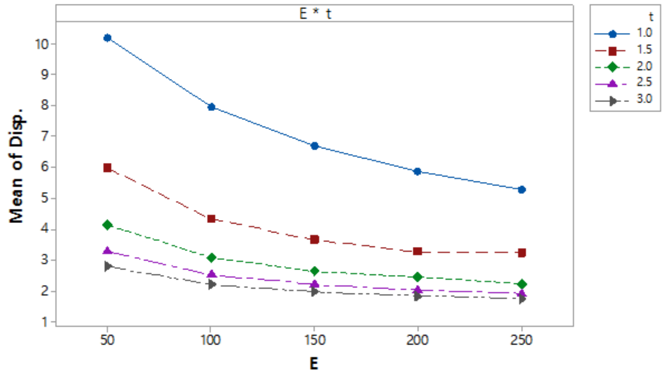


Figure.11 Interaction plot for deformation

Lightweight optimization

Since the optimally designed bracket was presented in a specific shape and is extremely thin when compared to its length or width, the optimal design was performed based on the previously applied test specifications. The main factors affecting deformation, maximum stress, and component weight include the bracket's thickness (t) and material. Other factors, such as the size of the component or curvature of the folding area are against the purpose of or have little influence on the design. The design optimization of the bracket can be defined as in Eq. 3.

$$\begin{aligned} &\text{Minimize} \quad && \text{Mass (Bracket)} \\ &\text{subject to} \quad && \text{deformation} < 4.33\text{mm} \end{aligned} \tag{3}$$

According to the headrest safety regulations in the FMVSS 202a, the design should limit the deformation under given loads within 13 mm. Therefore, the safety factor (S = 3) was applied to set the limit. The initial design model weighed about 1 kg with a deformation of 2.02 mm when t = 2.5, E = 200 GPa.

DOE-based simulation results showed that each variable is in dependent. Moreover, the sensitivity of each factor to the def ormation was examined, along with the weight of factor. For weight reduction, this study found that the thickness should b e reduced and determined the minimum strength value at diff erent thicknesses with deformation not exceeding 4.33 mm to design for safety.

Table 5 Conditions of each factor according to Mass variation

Mass variation[%]	t [mm]	minimum value of E [Gpa]	Deformation [mm]
-20	2	56	4.32
-30	1.75	98	4.29
-40	1.5	150	4.31
-50	1.25	240	4.30

Further reduction in weight can be expected if material selection i s performed within the range of satisfactory strength levels depen ding on the density of the material.

CONCLUSIONS

The findings of this study can be summarized as follows.

1) This study proposed a headrest module that shifts as the seatb ack rotates in folded condition and verified through trajectory analysis that the headrest did not collide with the front seat.
2) This study conducted simulations for static test requirements of the U.S. headrest safety standard FMVSS 202a and verifie d structural stability.
3) This study showed the correlation between the thickness of a bracket, which is part of the proposed mechanism, and its ph ysical properties to achieve the goal of bracket lightweight.

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