Optimization of Roof Drumming Noise between Roof Bow and Roof Panel in a Small Utility Vehicle

K. Saravanan[1], Rajendra Deokar[2], Nitin Nigul S[3], Ingale Nilesh[4], Namani Prasadbabu, Lal kundan[5]

IIT Madras, India

ABSTRACT

The roof panel and roof bow are critical components of the Body-in-White (BIW) structure, significantly influencing vehicle strength, durability, and NVH (Noise, Vibration, and Harshness) performance. Poor design in these areas can lead to NVH deterioration, resulting in discomfort for occupants. The roof bow must meet key functional requirements such as durability, fatigue resistance, and noise control under normal operating conditions. Incorporating design considerations early in the development phase such as material selection, geometry, and joining techniques can help shorten the product development timeline for OEMs. Adopting a "first-time-right" approach enables efficient optimization of the roof bow design, ensuring performance targets are met while also achieving long-term cost savings.

This paper describes the robust and optimal design for standard roof panels and roof bows of small utility vehicles. The structure meets the required operating conditions for durability and passes NVH target above 20 Hz. Finite element models are developed with different control factors that influence structure design. In this paper evaluates the impact of each component on the noise produced by the drumming of the roof and demonstrates how the integration of multiple factors can be skilfully utilized to create an ideal and resilient design that remains lightweight in the context of vehicle operation conditions. The final robust and optimized FEM design is proposed to eliminate the roof drumming noise in the small utility vehicle.

Keywords: Roof bows & panel, FEM, Modal frequency, and Roof drum noise

INTRODUCTION

As a rule of thumb in the automotive industry, a body in white (BIW) design that is lightweight, and high performance can be achieved with lightweight materials which is having high-strength steel or ultra-light steel [1-3]. However, if use the high strength material, the price of these material limits their application in BIW. As an effective alternative method is to optimize the structural design which is having the potential to achieve the lightweight and heigh performance design of BIW which is saving the cost. To solve this problem, the optimization -based design methods have been required in the vehicle to meet the customer comfort [4-5].

The primary objective of these studies is to achieve optimized design. In deterministic optimization, all design variables are assumed to be precisely defined. However, in practical engineering applications, uncertainties and ambiguities often arise. As a result, solutions derived from deterministic methods may violate established constraints when applied in real-world scenarios. In the automotive industry, improper design can lead to deterioration in Noise, Vibration, and Harshness (NVH) characteristics, affecting vehicle performance and passenger comfort. Therefore, continuous improvement in design and development across various aspects of automobile engineering is essential. Many technical innovations have already been successfully implemented in the automotive field, and numerous advancements are currently underway. Finite Element Analysis (FEA) has significantly contributed to the design process by reducing the time required for design validation and offering robust engineering solutions. These techniques enable engineers to evaluate complex systems efficiently and enhance the overall quality and reliability of automotive components.

As computing power continues to grow, the design of intricate engineering systems becomes more and more focused on the computer [6]. Finite element models are used extensively in the automotive industry. One of the

most critical attributes for vehicle product design is Noise, Vibration, and Harness (NVH) [7,8]. While there isn't a compulsory regulation like auto safety crashworthiness, vehicles exhibiting favourable NVH characteristics often lead to significantly enhanced customer satisfaction [9]. A vehicle system comprises various subsystems or components. It is crucial to carry out design optimization to lower development expenses and accelerate the time-to-market during later phases [10]. Likewise, optimizing the vehicle's BIW design is a systematic approach to achieving a lightweight vehicle design while fulfilling all NVH requirements. In the realm of optimization, despite the considerable advancements in computer speeds, the simulation duration of complete FE models remains excessively lengthy for direct design optimization. A single FE simulation run can occasionally take hours or even days to complete. Therefore, response surface methodology (RSM) is frequently employed as a proxy for the FE model to enhance efficiency. Xuepeng Qin et al. [12] explored structural acoustics analysis and performed optimization of an enclosed box-damped structure utilizing response surface methodology. By employing response surface techniques, Azadi et al. [13] enhanced the vehicle's NVH performance. An algorithm was also suggested to improve the overall NVH characteristics of the vehicle To mitigate vibration, Siva Sakthivel [14] predicted vibration amplitude resulting from machining parameters through response surface methodology. A recent investigation into the NVH performance of body panels was conducted by Balasubramanian et al. [15]. Analyzing existing literature reveals that, while response methods have demonstrated their efficacy, they are not yet extensively adopted in the development and refinement processes within the NVH domain. Furthermore, in the majority of current NVH performance optimization designs, dynamic response peaks are rarely accounted for using approximation models. Additionally, during the design optimization phase, there is limited research on model predictions and enhancement designs of body structures in the early stages of development.

The roof panel and the roof bow are the main components of the body-in-white (BIW), it has a significant impact on the vehicle strength & durability performance criteria and leads to NVH deterioration, which creates discomfort for the human body. To meet the customer expectation, we need to develop optimal design of roof bow and roof panel structure, which meet the functional objectives of durability, fatigue as well as to avoid roof drumming noise when the vehicle passing through pothole and vehicle running at normal operating conditions.

This paper presents a robust and optimized design approach for standard roof panels and roof bows in small utility vehicles. The proposed structure is engineered to meet durability requirements and achieve NVH (Noise, Vibration, and Harshness) targets above 20 Hz. Finite element models (FEM) are developed by incorporating various control factors that influence structural performance. A virtual simulation analysis is conducted to evaluate the interaction between standard roof bows and the overall roof structure. The roof performance is influenced by multiple parameters, including Roof material and thickness

- Roof bow geometry and positioning

- Number of roof beads

- Contact conditions between roof bows and the roof panel

- Cross-sectional profile of the roof panel

- Height of the roof bows

These factors collectively determine the structural integrity and acoustic behaviour of the roof system.

PROBLEM DESCRIPTIONS

When the SUV vehicle running at low speed on a bumpy asphalt surface, passengers in the rear experience a noticeable sensation of ear pressure, resulting in discomfort, along with a drumming noise that is reported. This concern has prompted a study and analysis of previous designs to identify the root cause and propose solutions. Notably, low rotational speeds are mainly noted between 1500 rpm and 3000 rpm; however, the subjective sensations inside the vehicle are experienced at lower vehicle speeds. In contrast, the sensation of ear pressure becomes significantly more pronounced when the vehicle operates at specific low speeds, and the roof drumming noise is linked to panel vibrations on uneven road surfaces, which is considered unacceptable. To

tackle the roof drumming noise issue in SUV vehicles, an optimal structural design approach has been thoroughly studied and analysed.

MODAL ANALYSIS THEORY

Modal analysis theory encompasses both real and complex modal approaches. The real modal theory is applied to undamped systems, whereas complex modal theory is essential for analysing systems with damping effects [16,17]. Due to the intricate nature of structures with numerous degrees of freedom, simplifying the analysis becomes crucial. For discrete linear vibration systems with a limited number of degrees of freedom, the state-space analysis method is commonly employed. The governing differential equations for the system under forced vibration conditions are given by:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{f(t)\}$$

In this context, [M], [C], and [K] represent the mass, damping, and stiffness matrices of the system, respectively. The vector {x} denotes the generalized displacement, while {f(t)} represents the external excitation force. The solution involves determining the eigenvalues and eigenvectors, which correspond to the modal frequencies and their associated mode shapes. In practical applications, only a subset of modes significantly contributes to the system's dynamic response—these are referred to as effective modes. Typically, the number of effective modes is smaller than the total number predicted by theoretical calculations. To prevent overwhelming negative impacts, like noise interference that can complicate the equations of morbidity, it typically employs the primary decomposition method, which involves reducing the matrix rank. To check the accuracy of finite element calculation model, need to do a modal test verification, of modal correlation analysis [18-20]. For a linear system with n degrees of freedom, the first-order theoretical and experimental modal shapes are represented as points in an n-dimensional real vector space R^n. Let
X= {x_1, x_2, x_3,…,x_n}$X=\{x1, x2, x3, ,x_n\}$ be the theoretical modal shape vector

Y= {y_1, y_2, y_3,…,y_n} $Y=\{y1,y2,y3,…,y_n\}$ be the experimental modal shape vector

The inner product of these vectors is defined as:

$$(X,Y) = \sum_{k=1}^{n} x_k, y_k$$

The correlation coefficient between the two modal shapes is given by:

$$C_p(X,Y) = \frac{|(X,Y)|}{\sqrt{(X,X) - (YY)}}$$

This coefficient Cp (X, Y) ranges from 0 to 1. A value closer to 1 indicates a strong correlation between the theoretical and experimental modal shapes, suggesting that the dynamic characteristics of the mode are well captured by the model.

GEOMETRY MODELLING OF ROOF AND ROOF BOW SUV VEHICLE

Normally geometric modelling of an SUV's roof and roof bows involves creating a 3D representation using software like CATIA or Fusion 360. This process typically starts with a base styling surface and then incorporates features like roof rails, bow roofs, and other reinforcement elements. The modelling process involves offsetting surfaces, creating curves, sweeping edges, and using boolean operations to define the final shape. Particularly in this paper to address this concern the existing design re modified without disturbing the styling surface I meant a styling surface provided by the design team, which defines the overall shape of the roof panel. Front roof rails involve offsetting the roof surface and splitting it with parallel curves, creating a base for the rail. Edges are swept to form the side surface, and then the rail is finalized through trimming and

offsetting roofs bow, which provided reinforcement are often modelled by sweeping curves and adding the fillets to create a smooth, curved shape. The base roof bow design was having smaller width, and it was two of them front and remaining two at the rear side which is shown in fig1.
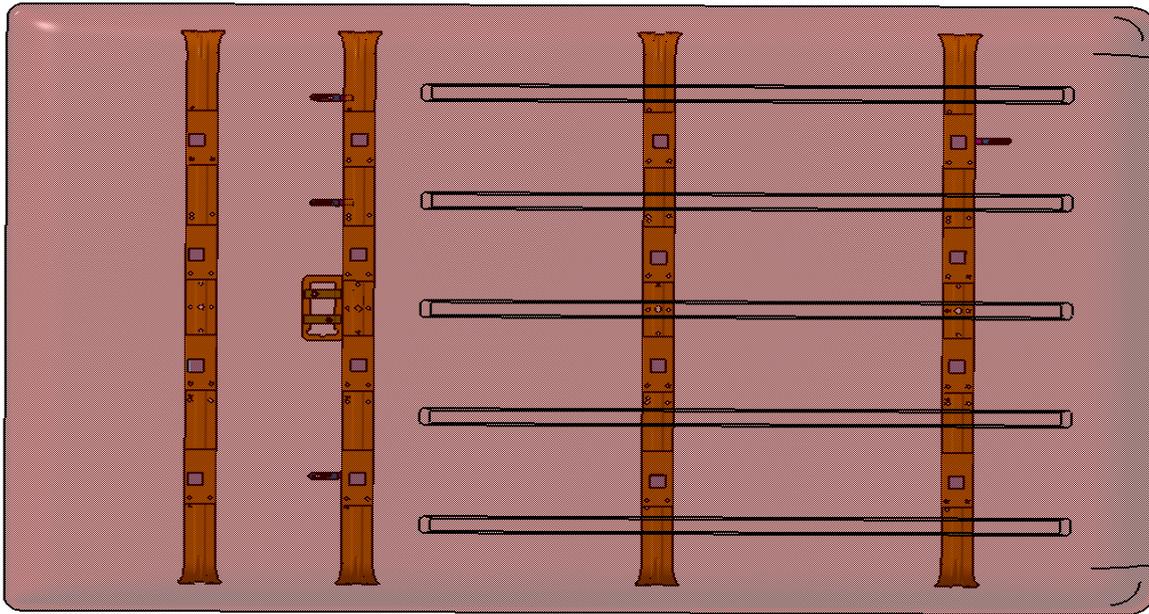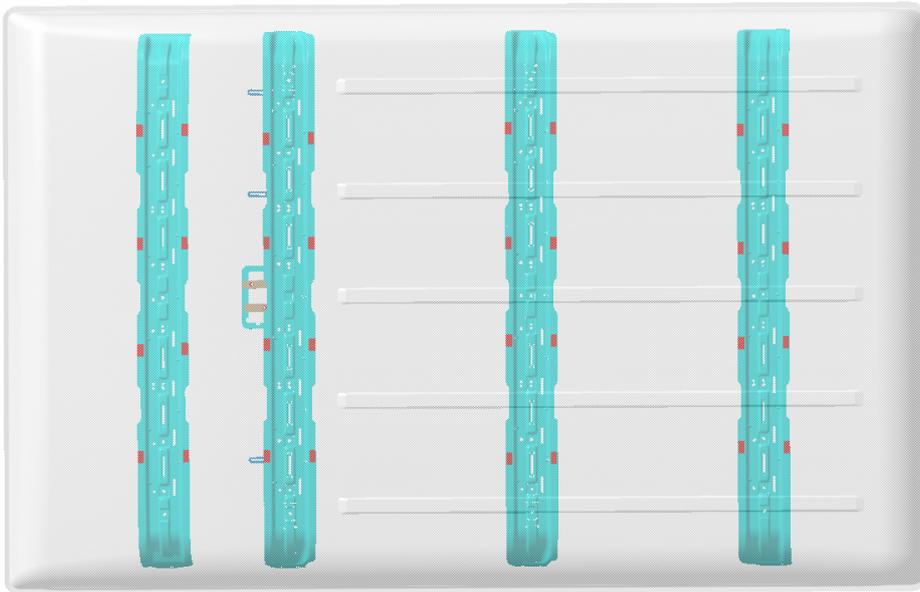

a)   Assembly design of roof bow & roof panel with half with half beed
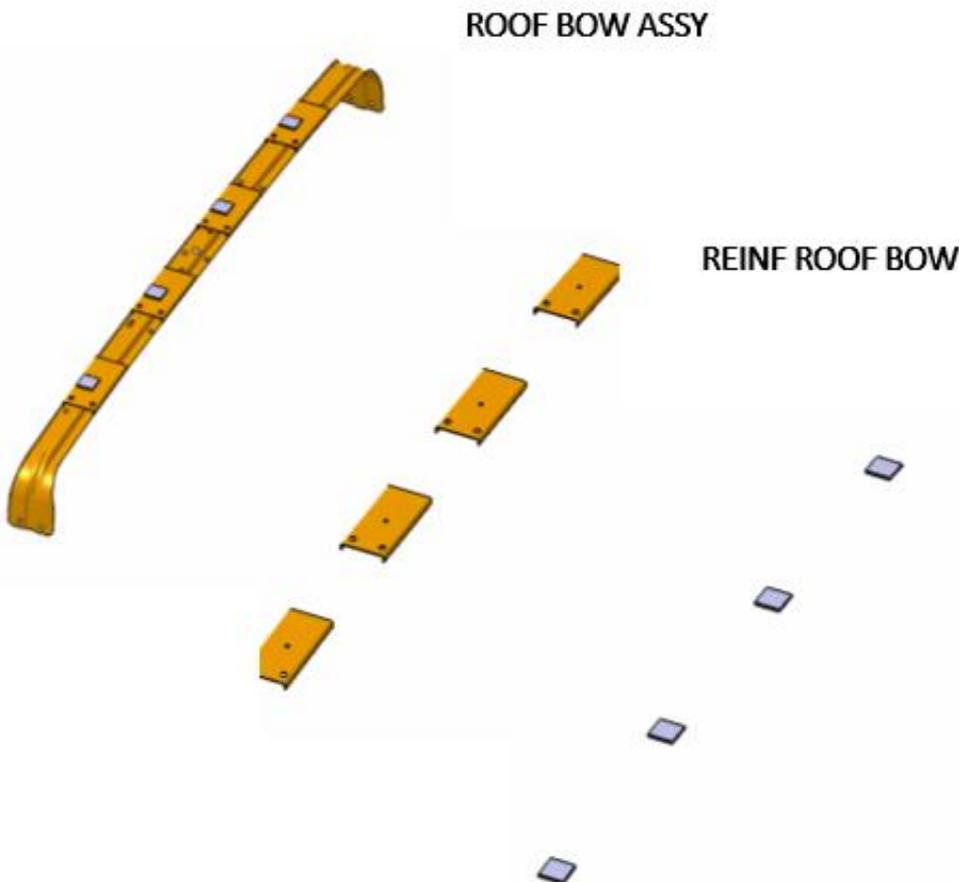
b) Exploded view of roof bow, reinforcement and structural sealant

Fig1: Base model roof bow and roof panel with structural sealant

The connection between the roof bow and the roof panel is established using square-shaped mastic structural sealant, applied at four designated points on each roof bow. These application points are highlighted in ash colour in the base model. This sealant will expand after the BIW body undergoes baking, forming a square configuration and the size is 30L X 30W X 4 mm thick. To enhance the surface contact between the panel and the roof bow with the assistance of the structural sealant.

a)   Assembly design of roof bow & roof panel with half Beed

b)   Exploded view of roof bow, reinforcement and structural sealant

Fig 2: Proposed model roof bow and roof panel with structural sealant

This base model causes drumming noise; to mitigate this, we are increasing the surface contact area between the roof panel and the roof bow. We are redesigning the roof bow by widening it and reducing the thickness from 1 mm to 0.75 mm, as depicted in fig 2. We enhanced the surface connection between the roof bow and the roof panel at the 8 and 16 positions, respectively, and the outcomes have been analysed.

FINITE ELEMENTS MODELLING OF ROOF & ROOF BOW SUV VEHICLE

A commercial vehicle primarily consists of the body-in-white (BIW), doors, and interior and exterior trim components. Among these, the BIW forms the core structural framework of the vehicle and plays a critical role in defining its structural characteristics. Therefore, modal analysis of the BIW is essential to determine the vehicle's structural modal parameters. The BIW is typically constructed by welding together sheet metal components, with most parts having a thickness of approximately 1 mm, and the maximum thickness generally not exceeding 3 mm. To perform finite element analysis (FEA), a detailed 3D CAD model must first be created. This model is then converted into a 2D mesh format and imported into Hyper Mesh for grid generation.

To enhance mesh quality and computational efficiency while maintaining accuracy, model simplification is necessary. Features such as small lugs, flanges, and minor openings which contribute minimally to overall stiffness can be neglected during modelling. The main body structure is meshed using four-node shell elements, while irregular geometries are handled using a combination of quadrilateral and triangular elements. Grid cell size is 10 mm, spot welding simulation precision of the model is very important, the use of high precision umbrella model to simulate the spot [8,9], establishing the finite element model of body in white with roof and roof bow with structural adhesive unit. In which the spot welds are modelled with ACM welds and Roof Panel adhesive given with teroson EV 6087 and the rigid connections are used for the simulation and the complete FEM model shown in fig3
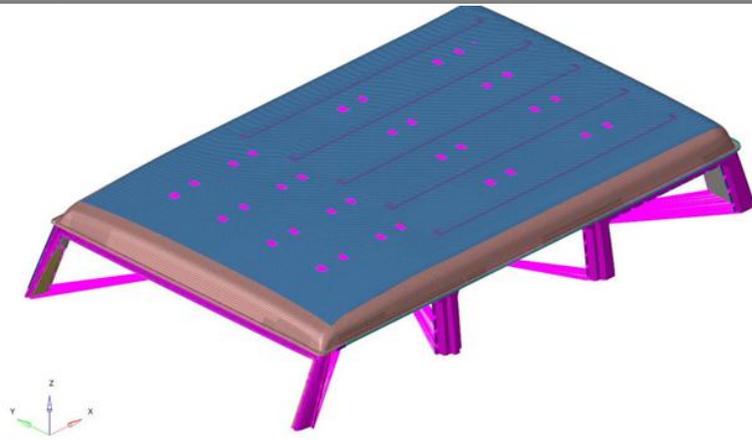
Fig3: Proposed model roof bow and roof panel with structural sealant

Using Nastran solver to BIW finite element model of the modal analysis in fix-fix condition has been evaluated. The simulation results show that the cut section of roof first two modal frequencies captured for both base as well proposed roof design model. The identical mesh model has been utilized for NVH analysis to assess the structure-borne noise in the roof panel region. To analyse the structure-borne noise vibration transfer function (VTF), this model has been employed.
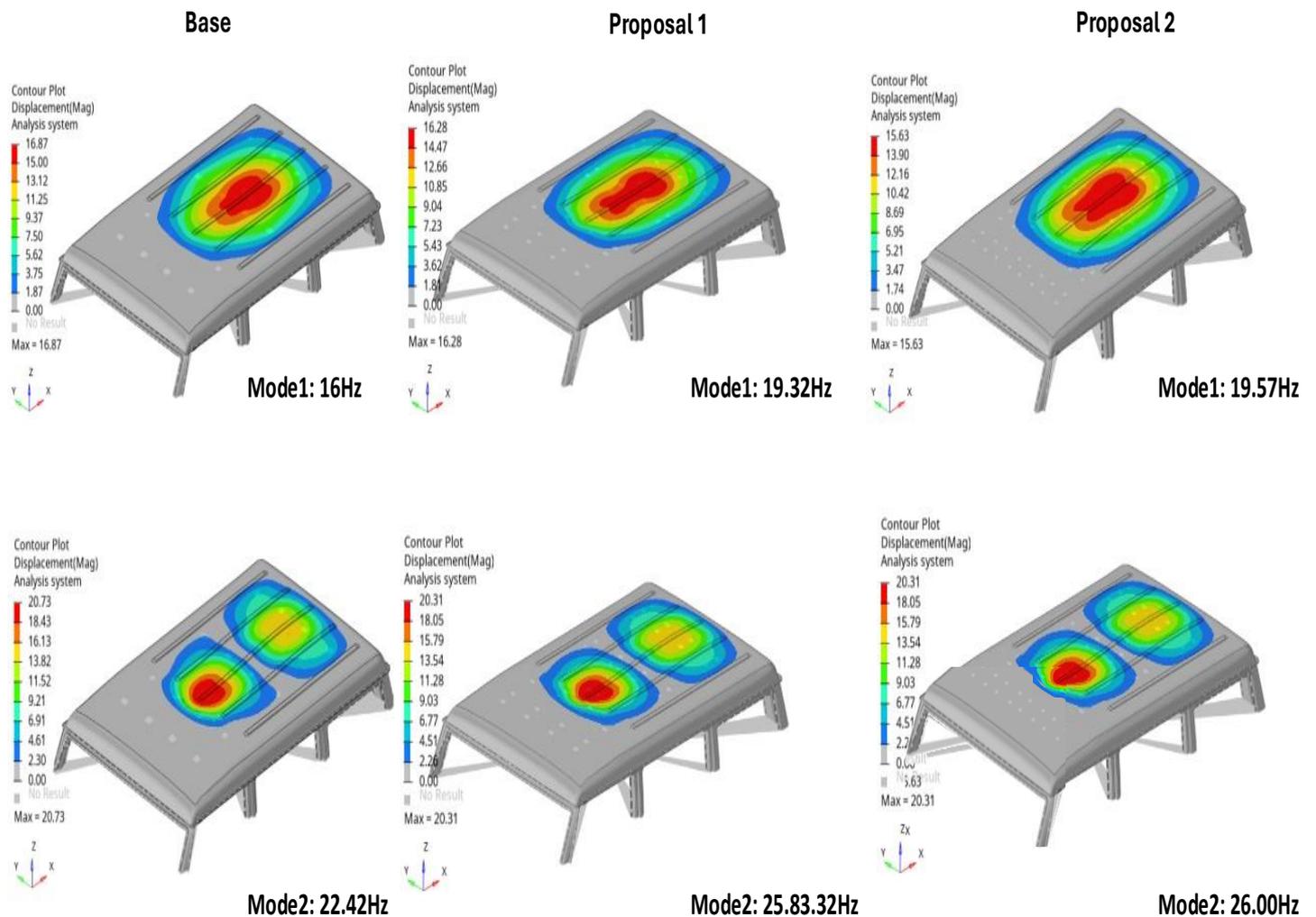

Fig 4. The model deflection shape of roof bow and roof panel with structural

The VTF illustrates how a vibrating system reacts to two external forces, quantifying the correlation between

input and output vibrations. Essentially, it indicates how effectively a forcing vibration can generate an excited vibration within a system. The VTF is commonly expressed as a ratio of the dynamic output to the dynamic input, often known as transmissibility.

RESULT AND DISCUSSION

The simulation scenarios listed in Table 1 have undergone modal analysis under fixed-fixed conditions, and the findings are presented in the table1. According to the simulation results, it is evident that the base model exhibits a lower natural frequency, which results in drumming noise during operational conditions. However, proposals 1 and 2 show a significant shift in natural frequency compared to the base model, as indicated in the table1. In proposal 1, the section of the roof bow has been enlarged to enhance surface contact between the roof panel and roof bow with the aid of structural sealant. In proposal 1, the structural sealant 30L × 15W × 4mm thickness is applied at 8 locations for each roof bow, while in proposal 2, the structural sealant 15L × 15W × 4mm thickness is applied at 16 locations for all roof bows. The modal frequency does not differ significantly between proposals 1 and 2, as the square-shaped structural sealant size is reduced to 15L × 15W × 4mm thick. The deflection shapes for the first two modal frequencies of both the base and proposed models are illustrated in fig 4.

Both proposals 1 and 2 demonstrate substantial enhancements in natural frequency compared to the base model. The same model has also been employed to assess the structure-borne noise in the cut section of the roof panel, as shown in fig 3. Based on the specified unit excitation at the centre of the roof panel, vibrations are recorded at the desired locations. As indicated in the paper, transmissibility is calculated using input and output vibrations, which is displayed in a fig 5.
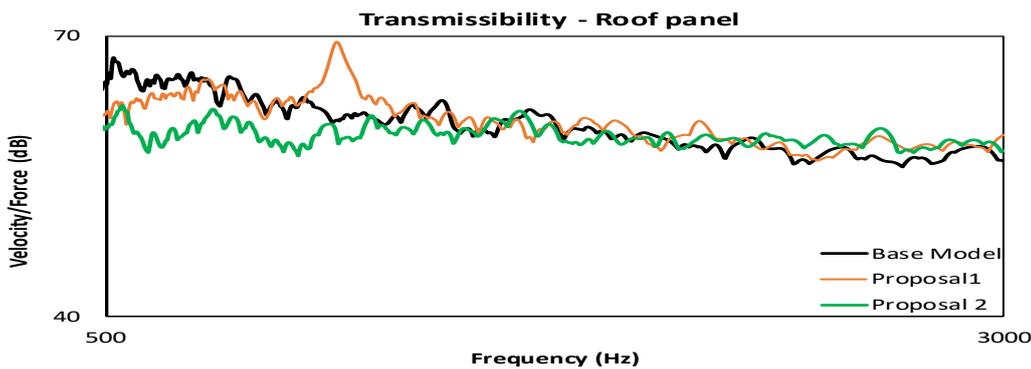

Fig 5. Transmissibility of roof bow and roof panel with structural sealant

S.No	Model Type	First natural frequency, Hz	Second natural frequency, Hz
1	**Base Model,** (half bead, square type sealant, roof bow thickness 1mm, 4 locations	14.36	22.42
2	**Proposal1**, (half bead, square type sealant, roof bow thickness 0.75mm, 8 locations	19.32	25.83
3	**Proposal 2**, (half bead, cylindrical type sealant, roof bow thickness 0.75mm, 16 locations	19.57	26.0

Table 1. Modal analysis of roof bow and roof panel with structural sealant

Proposal 2 exhibits lower structure-borne noise in comparison to the base model and proposal 1. In the transmissibility curve, a lower value indicates a more effective reduction in roof drumming noise. Although there is no significant frequency difference between proposals 1 and 2, proposal 2 yields better results in minimizing roof drumming noise due to the increased contact area between the panel and roof bow

SUMMARY/CONCLUSIONS

This paper assesses the influence of each component on the noise generated by the roof's drumming and

investigates the optimal design of the roof bow with square-shaped structural sealant. Finite element and VTF simulation modelling have been developed for various proposals, and the results are analysed.

1. Proposal1, which provides significant enhancement in the first mode frequency compared to the baseline model, also helps in minimizing the roof drumming noise.

2. Proposal2, which offers improved results in the first mode frequency relative to both the baseline and proposal1 models, while also reducing the roof drumming noise.

According to the research, Proposal 2 offers valuable insights for designers aiming to create a robust design to mitigate roof drumming noise in future SUV models

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