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ABSTRACT

Stability and structural integrity are extremely important in the design of a vehicle. Structural foams, when used to fill body cavities and joints, can greatly improve the stiffness of the vehicle, and provide additional acoustical and structural benefits.

This study involves modal testing and finite element analysis on a sports utility vehicle to understand the effect of structural foam on modal behavior. The modal analysis studies are performed on this vehicle to investigate the dynamic characteristics, joint stiffness and overall body behavior. A design of experiments (DOE) study was performed to understand how the foam's density and placement in the body influences vehicle stiffness. Prior to the design of experiments, a design sensitivity analysis (DSA) was done to identify the sensitive joints in the body structure and to minimize the number of design variables in the DOE study.

INTRODUCTION

Structural foam materials are two phase material systems which contain a solid phase (matrix) and a fluid (gas) phase. These foam materials, when injected in automotive cavities, reduce the body vibration amplitude[1], prevent noise transmission[2], and increase occupant impact protection[3]. This system of using structural foam in automotive joints or body cavities has many acoustical and structural benefits, and can provide many other improvements including crash-worthiness and fatigue resistance.

In this study, finite element analysis (FEA) and modal testing was used to evaluate the dynamic performance of structural foam on a sports utility vehicle's vibration modes. A body-in-white subsystem was used to evaluate the foam's effect on the vehicle body[4]. A baseline FEA model was developed and compared with modal testing results using a free-free boundary condition[5]. The design sensitivity analysis was conducted by using the FEA model with MSC/Nastran[4,6,7] in order to identify the sensitive joints and reduce the experimental design variables. The FEA model was then used to conduct the design of experiments with various foam densities and placements in the body, thus producing an optimal design. The design parameters considered were: total foam weight, density of foam, foam injection locations, modal frequencies, and modal shapes. The foam was then injected into the vehicle body at the designated locations, and the modal testing was repeated using the same conditions as the previous test.

FINITE ELEMENT MODEL AND VALIDATION

A body-in-white finite element model was developed to represent the vehicle. The real Lanczos method was used to extract the normal modes of the system[6]. A free-free boundary condition was used while the frequency range considered was from 0 to 100 Hz. The torsion, bending, pumping, front-end bending modes and two roof modes were observed within first five global modes. These five modes were used as the design modes for the foam optimization.

The modal testing was performed by using two shakers to apply an uncorrelated random force on the body, over the frequency range of 1 to 100 Hz. To excite the symmetric and asymmetric global modes of the vehicle, the shakers were mounted to the driver's side rail near the front bumper, and the passenger's side rail near the rear bumper. Linearity of the vehicle body was verified and the force applied was chosen to be 1 pound force for each shaker. To compare results easily with the FEA model, air-mounts were used to support the body and simulate a free-free boundary condition. Precautions were also taken to ensure that the rigid body modes were significantly less than the first mode of the structure. Tri-axial acceleration measurements were taken at 128 locations to give frequency response functions. The frequency response functions were then analyzed using time domain curve-fitting techniques to give the body's modal frequencies, structural damping and modal shapes.

Table 1 shows a comparison between the modal test and the finite element model's predictions before the foam application. Due to the adequate correlation between the FEA model and the test, the model was used for further predictions using structural foam.

Table 1. Comparison of Results for Baseline Vehicle (Before Foaming)

Mode #	Vehicle Test Freq (Hz)	Vehicle Test Description	FEA Model Freq (Hz)	FEA Model Description
1	24.76	Roof 1^{st} Bending	24.96	Roof 1^{st} Bending
2	26.83	1^{st} Torsion	25.16	1^{st} Torsion
3	30.77	Roof 2^{nd} Bending	31.29	Roof 2^{nd} Bending
4	34.66	Pumping + Front End Bending	34.28	Pumping + Front End Bending
5	37.29	1^{st} Vertical Bending	36.30	1^{st} Vertical Bending

DESIGN SENSITIVITY ANALYSIS

The design sensitivity analysis was done to find the most effective foam application locations[4,8]. After the structural foam is injected into a cavity, the material expands to form a block of foam perfectly bonded to the sheet metal. To determine the foam application locations, a structural layout optimization approach was developed[9].

The design parameters for this study were: foam density, location, total foam mass, and the modal frequency. Mode tracking was used for the first five design modes. The design domain was limited to the body cavities and joints, while the foam density varied from 2 to 24 lb/ft^3.

To predict the stiffness properties, a relationship was developed between Young's modulus of foam and density. Several empirical and theoretical models have been developed to describe the mechanical behavior of foam[10, 11]. These models were in close agreement with test data collected for this foam; however, long computational time was encountered using these models in the design sensitivity analysis. To speed up the process, an empirical linear function was developed to describe the relationship of the Young's modulus of the foam and the density. The empirical linear function can be expressed by:

$$\mathbf{E}=1637\rho$$

As show in Figure3, the intersection point, where ρ_0=18lb/ft^3, is the initial foam density for the sensitivity analysis. This simple linear function can speed up the design sensitivity analysis processes; but also induce a variation with actual material test data. The variation due to this simplification can be corrected later in the design of experiments[9]. The design sensitivity analysis was therefore, used to detect a trend of the foam's effect.

From the DSA results, the effective areas were identified and numbered as different joints, as shown in Figure 1. The most effective areas for foam application are joints 4, 5, 7, and 8; and the most sensitive components were found to be the A-pillar and D-pillar.

DESIGN OF EXPERIMENTS

RANKING OF JOINTS – To optimize the foam application, ranking of the joints was performed. In this study, modal analysis was used to evaluate and rank the joints. Modal analysis was performed using 8 lb/ft^3 foam in each joint separately, one joint at a time[4]. To rank the joints, the percent increase in modal frequency between the foam filled joint case and the unfoamed case (baseline case) was calculated. These overall results were averaged over the first 5 modes and are shown in Figure 2 below.

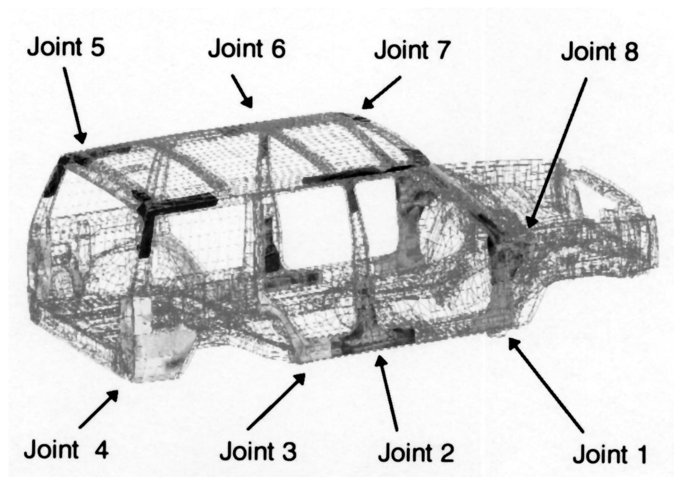

Figure 1. Joints Studied in the Process

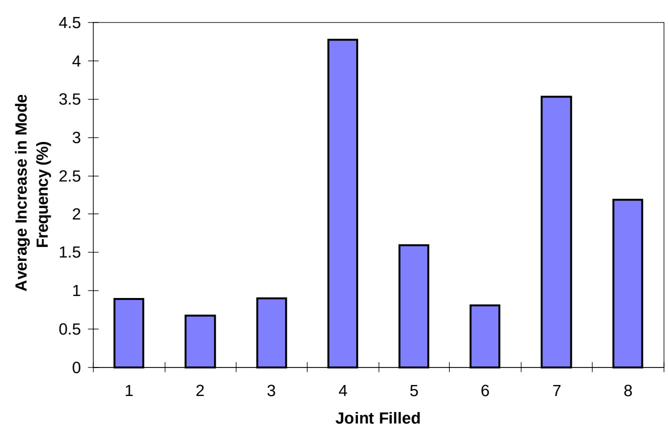

Figure 2. Ranking of Joints

From these results, it is clear that joints 4, 7, 5, and 8 affect the body stiffness the most. This joint ranking analysis verified the DSA results.

FOAM DENSITY – Different densities of structural foam were considered to stiffen the vehicle body. Figure 3 shows how the modulus of foam varies with the foam's density, and the simplified linear function used in the design sensitivity analysis.

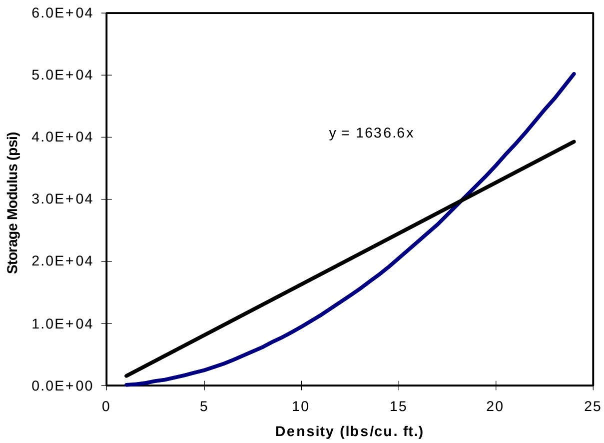

Figure 3. Modulus Variation with Foam Density

Finite element analysis was used to study foam with densities of 8, 12, and 24 lb/ft^3 in the body. In these cases, the material properties from measurements were used(and not from the linear function). Since the modulus of foam increases with density, the stiffness of the body also increased using a higher density of foam. Figure 4 shows the total performance benefits observed from the model's modal frequencies with added foam to the joints. The data points in Figure 4 are the foam mass for 8, 12 and 24 lb/ft^3 foam respectively.

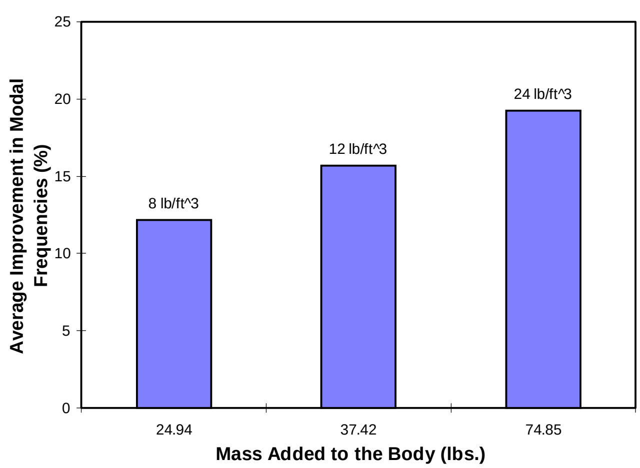

Figure 4. Average Improvement Using Different Densities

Structural foam with a density of 8 lb/ft^3 was used for the foam application because it had the highest stiffness improvement per pound mass[4]. The total mass of structural foam added to the vehicle body was about 25 lbs. The finite element analysis results for the 8 lb/ft^3 foam application is shown in Table 2 below.

Table 2. Improvement in Modal Frequencies from FEA Model

Mode #	**Baseline Frequency (Hz) & Mode Description**	**with 8 pcf Foam Frequency (Hz) & Mode Description**
1	24.96 Roof 1st Bending	27.05 Roof 1st Bending
2	25.16 1st Torsion	31.82 Roof 2nd Bending
3	31.29 Roof 2nd Bending	34.52 1st Torsion
4	34.28 Pumping + Front End Bending	36.02 Pumping + Front End Bending
5	36.30 1st Vertical Bending	42.04 1st Vertical Bending

TESTING RESULTS

Modal testing was performed on the foamed body using the same test setup and conditions as the baseline test. Many of the same modes were present after the vehicle was foamed, only the modal frequency was increased, as expected. The results of the modal tests are shown in Table 3 below.

Table 3. Foam's Effect on the Vehicle

Before Foaming			**With 8 pcf Foam**		
Mode	**Freq (Hz)**	**Shape**	**Mode**	**Freq (Hz)**	**Shape**
1	24.76	Roof 1st Bending	1	28.41	Roof 1st Bending
2	26.83	1st Torsion	2	31.48	Roof 2nd Bending
3	30.77	Roof 2nd Bending	3	34.64	1st Torsion
4	34.66	Pumping + Front End Bending	4	35.78	Pumping + Front End Bending
5	37.29	1st Vertical Bending	5	45.86	1st Vertical Bending

The torsional mode was significantly affected by the structural foam, shifting it from 26.83 Hz to 34.64 Hz, a 29.1% increase. The roof 2nd bending and the pumping modes were not significantly affected by the structural foam. This is because a majority of motion of these modes did not involve the components that were foamed. The greatest improvement was noticed in the modes which involved motion of the pillars and joints. Figure 5 shows the increase in modal frequencies for the modes found in both the baseline and foamed case. Figure 6 shows the frequency response function for the vehicle body (summed from all the acquisition points) with and without foam.

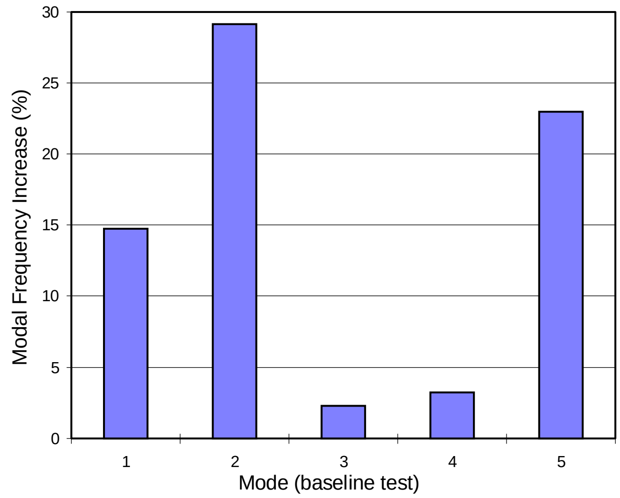

Figure 5. Increase in Modal Frequency

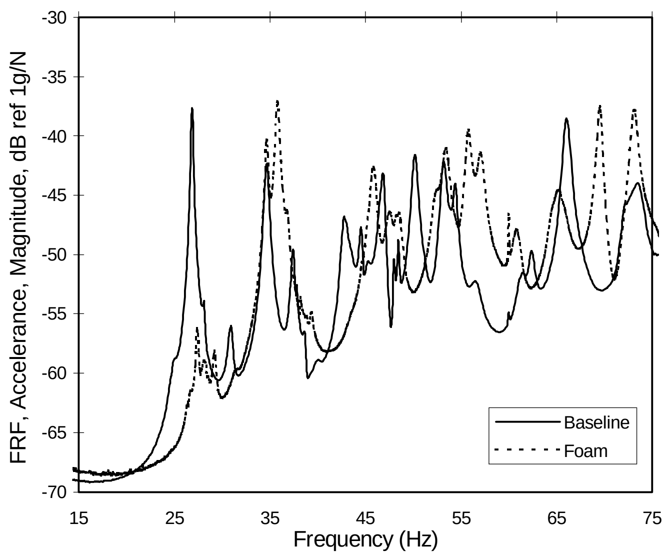

Figure 6. Frequency Response Functions for Body with and without Foam

CONCLUSION

The most sensitive areas of the body were found to be the A-pillar, the D-pillar, and their joints. With structural foam injected into these sensitive areas, the vehicle body was significantly stiffened, as shown by the increase in modal frequencies. The 1st torsional mode was most affected with an increase of 29.1% in modal frequency.

The design sensitivity analysis and design of experiments described here, can be used to identify the sensitive areas of the body structure. These results are useful in the determining the best application locations for structural foam.

Further work will be done to determine the influence of different density foams based on this approach for a fully-assembled vehicle. The fully-assembled vehicle will be evaluated using laboratory and road testing.

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