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NOISE AND VIBRATION

CONFERENCE & EXHIBITION

**THE IDENTIFICATION OF MINIMUM WEIGHT SOUND
PACKAGES THAT MEET SPECIFIED VEHICLE
INTERIOR SOUND PRESSURE LEVELS**
(SAE Technical Paper 2019-01-1504)

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OBJECTIVE

- **Minimize The Weight Of A Sound Package By Balancing Absorption And Transmission Performance**

- **Impact Of A Weight Optimization Of The Sound Package In The Automotive Industry**

Total weight reduction → Improve gas mileage (Battery mileage) beyond current levels

Conventional sound package for a luxury vehicle → about 120 lbs

PREVIOUS WORK

Hyunjun Shin and J. Stuart Bolton, "The Identification of Minimum-weight Sound Packages," *Noise Control Engineering Journal*, 66(6), pp. 523-540, (2018).

INTRODUCTION

SOUND PACKAGE LAYOUT

Engine
Compartment

Vehicle Interior

SAP CALCULATION

$$\frac{\sum_{n=1}^{51} \sqrt{\text{Re}(P_n)^2 + \text{Im}(P_n)^2}}{\text{Total \# of Points}}$$

OPTIMIZATION PROCESS

EQUIVALENT FLUID

SAP CALCULATION

TARGET SAP

SELECTION

GA OPTIMIZER

Flexible MPP

$$\sigma_{low} \leq \sigma_{MPP} \leq \sigma_{up}$$

$$m_{low} \leq m_{MPP} \leq m_{up}$$

Limp porous Layer

$$\sigma_{low} \leq \sigma_{porous} \leq \sigma_{up}$$

$$m_{low} \leq m_{porous} \leq m_{up}$$

Error Function

$$E = \left| 1 - \frac{SAP_{Current}}{SAP_{Target}} \right|$$

OPTIMIZATION RESULTS

LIGHTEST Combinations

HEAVIEST Combinations

POSSIBLE Combinations

Optimization performed between 500 Hz and 4000 Hz

RESULTS

SAP (Pa) (dB)	MPP		Limp Porous		Total
	Surface Density (kg/m ²)	Flow Resistance (MKS Rayls)	Surface Density (kg/m ²)	Flow Resistance (MKS Rayls)	Surface Density (kg/m ²)
0.013 (56.3)	0.446	1397.3	0.2889	1178.1	0.755 (Lightest)
	2.907	1179.0	0.2337	829.5	3.141 (Heaviest)
0.016 (58.1)	0.3299	1420.2	0.1927	373.1	0.523 (Lightest)
	2.924	780.7	0.3924	258.3	3.317 (Heaviest)
0.019 (59.6)	0.311	864.2	0.0752	102.6	0.386 (Lightest)
	2.923	503.7	0.339	310.9	3.262 (Heaviest)
0.022 (60.8)	0.133	1040.1	0.139	1004.2	0.272 (Lightest)
	2.995	317.9	0.185	590.4	3.180 (Heaviest)
0.025 (61.9)	0.104	730.1	0.071	343.7	0.175 (Lightest)
	2.960	137.4	0.322	474.0	3.282 (Heaviest)
0.028 (62.9)	0.100	261.5	0.032	100.0	0.132 (Lightest)
	2.961	124.4	0.155	124.6	3.116 (Heaviest)

CONCLUSIONS FROM PREVIOUS WORK

- It was found that when the sound package consisted of an **aluminum panel**, and a **layer of fibrous material with a microperforated panel surface treatment**, the lightest **solutions tended to favor barrier performance over absorption performance**, and that the **majority of the mass and flow resistance tended to be given to the microperforated panel**
- It was found that the **total surface density required to meet a target sound pressure increased rapidly as the target level decreased**, thus suggesting that **the shape of the target spectrum should be designed carefully so that weight is not “spent” creating very low sound pressure levels in frequency bands that are not important from a sound quality point-of-view**

EFFECT OF BASE PANEL MASS

Aluminum to Steel Panel

Results

Steel panel case for various SAPs

SAP (Pa) (dB)					Surface Density (kg/m ²)
	Surface Density (kg/m ²)	Flow Resistance (MKS Rayls)	Surface Density (kg/m ²)	Flow Resistance (MKS Rayls)	
0.005 (47.9)	0.306	1434.9	0.132	1352.7	0.438 (Lightest)
	2.202	746.6	0.431	247.9	2.633 (Heaviest)
0.007 (50.9)	0.163	762.2	0.047	1493.0	0.210 (Lightest)
	2.689	161.5	0.257	1160.9	2.946 (Heaviest)
0.009 (53.1)	0.100	217.7	0.034	1481.8	0.134 (Lightest)
	2.888	121.8	0.062	989.7	2.950 (Heaviest)

Flexible MPP flow resistance decreases
Limp Porous Layer flow resistance increases
 → improving the absorption performance

EFFECT OF FREQUENCY A-WEIGHTING

A-weighting function is applied to SAP calculation

→ Emphasizes the SAP at higher frequencies (above 1000 Hz)

→ A-weighted SAP is then used for the weight optimization

Apply A-weighting Function

$$R_A(f) = \frac{12194^2 f^4}{(f^2 + 20.6^2) \sqrt{(f^2 + 107.7^2)(f^2 + 737.9^2)(f^2 + 12194^2)}}$$

$$A(f) = 20 \log_{10}(R_A(f)) + 2.00$$

EFFECT OF FREQUENCY A-WEIGHTING

Optimization performed between 100 Hz and 10000 Hz

A-weighting case

SAP (Pa) (dB)					
	Surface Density (kg/m ²)	Flow Resistance (MKS Rayls)	Surface Density (kg/m ²)	Flow Resistance (MKS Rayls)	Surface Density (kg/m ²)
0.007 (50.9)	1.943	1464.4	0.449	1493.3	2.392 (Lightest)
	2.999	1438.8	0.451	1018.6	3.450 (Heaviest)
0.01 (53.9)	0.407	1288.6	0.142	1388.5	0.559 (Lightest)
	1.639	1067.7	0.070	248.7	1.709 (Heaviest)
0.013 (56.3)	0.125	1011.9	0.114	1138.7	0.239 (Lightest)
	2.239	140.2	0.336	140.2	2.575 (Heaviest)
0.016 (58.1)	0.100	104.0	0.375	144.5	0.1375 (Lightest)
	2.955	385.8	0.145	100.0	3.100 (Heaviest)

COMPARISON – A-weighting vs Speech Interference Range

Lightest possible combinations

- A-weighting optimization → Lighter solutions

OBSERVATIONS

- **Light base panel – barrier performance is emphasized at the expense of absorption**
- **Heavier base panel – absorption performance is emphasized because of improved barrier performance of base panel**
- **A-weighted target spectrum reduces mass required to meet target**
- **Target spectrum has a large impact on surface density**
- **Large weight penalty if target levels too low: i.e., target “good” level, not “best possible” level**

FE MODEL OF MORE REALISTIC INTERIOR

- More realistic case which describes the vehicle interior volume.
- For the passenger vehicle
 - Head room : 1000 mm to 1100 mm
 - Leg room : 1000 mm to 1100 mm
 - Second Leg room : 800 mm to 1000 mm
 - Front of the car to the rear seat : 1800 mm to 2100 mm

OBSERVATIONS

- **Use of FE model in optimization procedure is prohibitively expensive compared to TMM/duct model**
- **Would be useful to perform optimization using TMM-duct model and relate those results to the levels in a more realistic interior geometry: i.e., translate target level in realistic geometry to target level in simple duct geometry**

CORRELATION BETWEEN A SIMPLE DUCT AND A REALISTIC MODEL

To make the a averaged absorption in the downstream section 0.3

Averaged Absorption Calculation

$$\overline{\alpha}_{Total} = \frac{\sum S_i A_i}{S}$$

S denotes the total surface area

S_i describes an area of each surfaces

$\overline{\alpha}_{Total}$ denotes the total absorption of the surface

A_i denotes the absorption of each surface

SAP [dB] Duct	56.3	58.1	59.6	60.8	61.9	62.9
SAP [dB] VLC	51.7	53.6	55.1	56.4	57.5	58.4

SAP for both cases are calculated and plotted

SAP [VLC] vs. SAP [Duct]

- SAPs of 10 different surface density combinations (A set of 10 lowest surface densities that gave the same SAP)
- Clear relation between SAP's in the two geometries

EMPIRICAL EQUATION DEVELOPMENT PROCESS

DATA COLLECTION

Straight Duct Case

Various SAP target & Absorption

- Sound Energy Density In The Cavity
- Sound Power Incident At Inlet
- Space-averaged Pressure In The Cavity

VLC Case

Various SAP target & Absorption

- Sound Energy Density In The Cavity
- Sound Power Incident At Inlet
- Space-averaged Pressure In The Cavity

FIND CORRELATION

Acoustic Properties

Various SAP targets & Absorption

- Sound Energy Density Ratio

$$\frac{E_{\text{Duct}}/A_{\text{Duct}}}{E_{\text{VLC}}/A_{\text{VLC}}}$$

- Space-Averaged Pressure Ratio

$$\frac{SAP_{\text{Duct}}}{SAP_{\text{VLC}}}$$

- Sound Power Incident Ratio [VLC Only]

$$\frac{P_{\text{VLC}}}{P_{\text{In,VLC}}}$$

- Sound Power incident Ratio

$$\frac{P_{\text{In,Duct}}/A_{\text{In,Duct}}}{P_{\text{In,VLC}}/A_{\text{In,VLC}}}$$

DEVELOPMENT

EMPIRICAL EQUATION

$$SAP_{VLC} = \frac{\bar{P}_{in,Duct} A_{in,VLC} A_{cavity,Duct} F_1(\bar{\alpha}_{VLC})}{\bar{P}_{Duct} A_{cavity,VLC} A_{in,Duct} F_2(\bar{\alpha}_{VLC}) F_3(\bar{\alpha}_{VLC})} SAP_{Duct}$$

SAP Error (%)				
SAP Target (dB)	Absorption			
	0.1	0.2	0.3	0.4
56.3	1.01	0.08	0.32	0.88
58.1	0.67	1.04	0.70	0.08
59.6	0.62	0.34	0.51	0.64
60.8	0.47	0.24	0.16	0.31
61.9	0.56	0.28	0.24	0.42
62.9	0.54	0.30	0.41	0.50

$$ERROR \% = \frac{ABS(SAP_{FEA} - SAP_{Prediction})}{SAP_{FEA}} * 100$$

Desired target level in VLC can be related in this way to target level in simple duct geometry

EFFECT OF TARGET AREA

Vehicle Interior includes :

Vehicle Interior Space In 3-D Representation

**Front & Rear Car Seats
Parcel Shelf
Front & Rear Carpets
Head Liner**

Vehicle Interior Space In 2-D Representation

EFFECT OF TARGET AREA

- Almost constant level difference in decibels between the two cases
- SAP of the total cavity of the vehicle interior can still be used as a metric to evaluate the acoustic performance of the sound packages, but with an adjustment to account for the spatial variation within the interior space.

CONCLUSIONS

- The **sound package** was modeled as an equivalent fluid by using the JCA model for both the **limp porous layer** and the **flexible MPP**
- **Genetic Algorithm** was used to find the various sound package property combinations
- It was shown that in the lightest sound packages, **barrier performance was favored over absorption performance**
- When mass of the metal panel was increased, balance shifted towards absorption
- **Shape and level of target spectrum** has significant impact on required mass
- **Finite Element tool** was used to evaluate the acoustic performance of the sound packages for a more complex vehicle interior geometry. By using the FE tool, the energy density, SAPs, and incident power were calculated to study the **correlation between the straight duct and the complex geometry cases**
- An **empirical equation** was developed that makes it possible to **estimate the SAPs in the complex geometry case by using the results from the TMM-based optimization in the straight duct case**

FUTURE NEEDS

- The analysis needs to be extended to **frequency-dependent impedances** so that the accuracy of the SAP calculations can be further improved
- The empirical equation needs to be improved **by implementing more exact correlation functions** rather than the linearized functions used here to estimate the SAPs in the complex geometry
- Finally, it would be useful, given adequate computational resources, to **extend the current procedure to three dimensions**

Thank you

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- **Presentation available at Publication of the Ray W. Herrick Laboratories (Herrick E-Pubs)**
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