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VERIFYING VEHICLE SEA MODEL PREDICTIONS FOR AIRBORNE NOISE TRANSMISSION USING DESIGNED EXPERIMENTS

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Introduction

Statistical Energy Analysis (SEA) is an approximate method to study noise and vibration transmission in complex systems. In SEA, a complex system is modeled as an assemblage of coupled subsystems. The fundamental postulate of SEA is that power flow between two coupled subsystems is proportional to the modal power difference of the two subsystems. While this is true for two linear resonators coupled by spring, mass and gyroscopic elements [1], extension to complex systems requires assumptions such as modal incoherence, equipartition of energy, etc. As a result, verification of SEA models in practical applications is essential.

This paper considers the SEA application in automobile high frequency noise and vibration analysis. A vehicle parametric SEA model was created. Its response predictions correlated well with measured results at selected locations [2]. Great care was taken in selecting measurement locations to insure that when the desired response was correctly predicted, the energy transfer path was also correct. However, due to the complexity of the model and the precision of measurements, it is impossible to design a test that will uniquely determine all the parameters in the model. Therefore, questions regarding the validity of the "correlated" SEA model still exist. Fortunately, no matter how complex the problem is, the main objective of any predictive tools is to be able to predict design changes. To assess the vehicle SEA model predictive capability, one-factor-at-a-time (OFAAT) experimental measurements of vehicle design changes were made. However, for the airborne noise transmission case considered, the variability of the measurements was on the same order of magnitude as the effect of the design changes. It was then concluded that the OFAAT experimental method could not be used. As an alternative, factorial designed experiments (DEX) were performed using hardware as well as the SEA model. The variance of the estimated effects of the design changes was calculated from the hardware experimental data, and served as a reference when comparing the measured results with the SEA predictions. The results of the hardware experiment agreed well with that of the SEA model while at the same time revealing areas of further model improvement.

Vehicle SEA Model

A vehicle SEA model consists of air space outside the vehicle which contributes to airborne noise transmission, vehicle interior space, structural components and sound package (i.e. non-structural components that attenuate interior sound level such as carpet, seats etc.).

The SEA modeling of a vehicle system begins with the subdivision of the system into sub-structures. Each sub-structure is idealized into one or more SEA subsystems. The SEA subsystems are connected with point, line and area junctions [1]. Each subsystem is assigned with appropriate material properties. Excitation to the system is identified either from vehicle operating conditions, or from laboratory test conditions.

A D-class vehicle trimmed body SEA model, validated using the modal power thermogram approach [2], was exercised to predict design modifications to reduce airborne sound transmission to rear seat passengers.

SEA Model Verification Using Designed Experiments

The Brainstorming Session. A group of experienced noise and vibration engineers had a brainstorming session and came up with an exhaustive list of 15 design changes which they thought would significantly affect the airborne sound transmission to the rear seat passengers. The 15 design changes were: (A). increased door gasket thickness, (B). added carpet under the rear seat, (C). covered rear shock tower caps, (D). increased floor carpet barrier thickness and density, (E). increased floor carpet fiber pad thickness, (F). increased trunk absorption, (G). increased headliner thickness, (H). sealed package tray openings, (I). added 1 lb/ft^2 carpet to trunk, (J). added sound insulation in rear wheel housing, (K). increased thickness and damping of back window, (L). increased thickness and damping of rear door windows and quarter windows, (M). added barrier between rear seat and trunk, (N). increased thickness and damping of wheel housing, (O). increased thickness and damping of floor panel.

The Screening SEA DEX. First, a $2^{(15-11)}$ fractional factorial experiment [3] was performed using the SEA model to rank order the effects of the 15 design variables. The five most important design variables determined from the SEA model are summarized in Table 1.

Table 1: Rank Order of Significant Effects

1/3 Oct. Band Ctr. Freq.	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
500 Hz				5					3		2	1	3		
1000 Hz							3	5			2	1	4		
2000 Hz						5	3	4			2	1			

Hardware Verification of the Most Important Effect (OFAAT). Second, since the design variable (L) was the most significant design change, a hardware OFAAT experiment was preformed to verify its effect. The rear door windows and quarter windows were covered with 2 lb/ft^2 lead backed foam and the SPL difference (effect) at rear seat passenger ears was recorded. In fact, Figure 1 shows the effect of covering all of the door windows and quarter windows with 2 lb/ft^2 lead backed foam as compared to the baseline condition. The test data in Fig. 1 suggests that the effect of the side windows is not evident and is well within the historical measurement variance of approximate 2 dB.

Hardware DEX of Multiple Effects. Third, since the OFAAT experiment was not able to measure the effect of the most significant design change, a $2^{(6-3)}$ hardware DEX was performed for the following six design changes: (1). increased trunk absorption, (2). taped door seams with lead tape, (3). covered rear door windows and quarter windows with 2 lb/ft^2 lead backed foam, (4). increased headliner absorption by adding 2 inches of foam, (5). covered back window with 2 lb/ft^2 lead backed foam, (6). covered rear door panel with 1 lb/ft^2 loaded-vinyl backed foam.

The six design changes were chosen because design variables 3, 4, 5 were important factors as determined by the screening SEA DEX, we had questions about model capability of the door seals, design variable 1 was easy to implement, and we wanted to verify if design variable 6 was truly unimportant. Table 2 shows the experimental design matrix for the six design variables 1 to 6.

Table 2: $2^{(6-3)}$ Experimental Design Matrix ("+" indicates the design variable was modified, "-" indicates the design variable was set to baseline condition)

Run ID	1	2	3	4	5	6
1	+	+	+	+	+	+
2	-	+	+	-	-	+
3	+	-	+	-	+	-
4	-	-	+	+	-	-
5	+	+	-	+	-	-
6	-	+	-	-	+	-
7	+	-	-	-	-	+
8	-	-	-	+	+	+

SEA Simulation of the Hardware DEX. The SEA model was used to simulate the hardware DEX so that direct comparisons could be made for all six design changes in order to assess the performance of the SEA model. The six design changes implemented in the SEA model were: (1). doubled the acoustic absorption in trunk, (2). removed the junction from outside air to door seal to passenger compartment, (3). removed the junction from outside air to rear door window and quarter window to passenger compartment, (4). increased headliner thickness by 2 inches and double its damping, (5). removed the junction from outside air to back window to passenger compartment, (6). removed the junction from outside air to door panel to passenger compartment.

It is important to note that changes in the SEA model do not exactly represent hardware test. The effect of removing a junction in the SEA model is to assume that there is infinite transmission loss through this junction. Therefore, the SEA DEX results served as upper bounds for design variables 2, 3, 5 and 6.

Comparison of Hardware DEX and SEA DEX. The SEA model correlated well with measurements for the case which had all six design changes. However, the model over estimated the coincidence effect of the rear door windows, quarter windows and back window (Fig. 2). Fig. 3 shows the effect of individual design change as compared with the experimental "noise" envelope. The "noise" envelope (shaded area) was calculated using Lenth's method [4]. A design change is significant if its effect lies outside the shaded area. Both the SEA model and hardware tests show that the headliner is important and the rear door panel is not important. The SEA model over estimated the trunk absorption effect, and the door seal model needs further improvement.

Conclusions

The validity of the SEA method in vehicle high frequency noise and vibration analysis has been verified. High frequency noise inside a vehicle is sometimes controlled by multiple noise transmission paths. A single design change will usually result in 1-2 dB improvement. Traditional OFAAT experiments are not able to evaluate the effect due to measurement variability. Factorial designed experiments accompanied with an experimental noise estimate help evaluate the "real" effect of practical design modifications.

Acknowledgments

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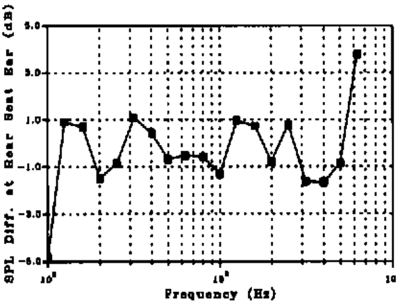

Fig. 1 Effect of Covering Side Windows

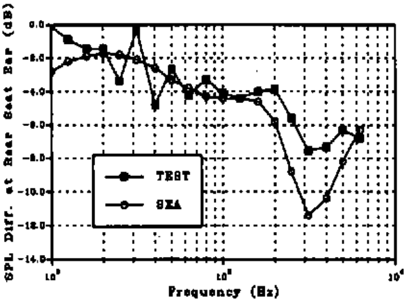

Fig. 2 Effect of All 6 Design Changes

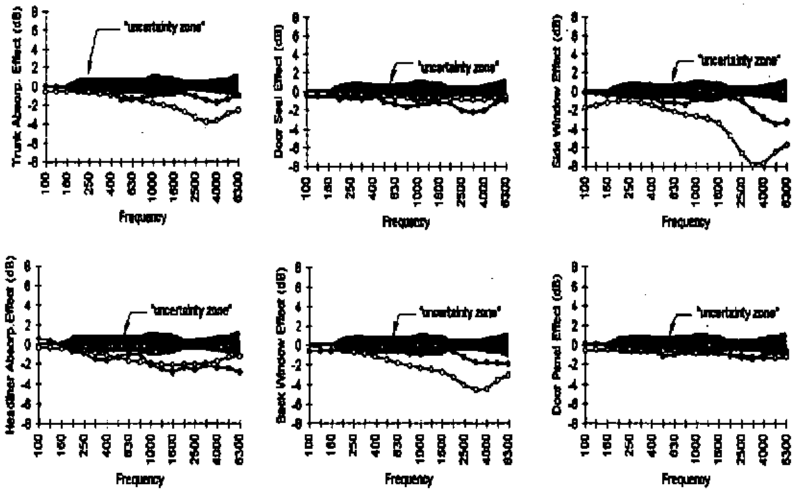

Fig. 3 Comparison of Design Change Effects: ● Hardware DEX, ○ SEA DEX

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