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A HYBRID SEA-MEASUREMENT TECHNIQUE TO PREDICT DRIVER'S EAR SPL FROM ENERGY FLOW THROUGH A VEHICLE DASH AND TRANSFER FUNCTIONS

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Abstract

Statistical Energy Analysis (SEA) is a very useful analytical design tool to predict the effect of sound package, construction, and pass-through design changes to automotive dash, floor, roof, and door structures. A validated SEA model can be used to identify the effect of changes to design variables and to determine the optimal combinations required to meet a particular component-level target. One of the current limitations of a purely analytical SEA technique is that the model can predict the amount of energy transmitted through a subassembly into the passenger compartment and can predict the mean acoustic response within the cabin as a summation of the energy through separate parts of the subassembly, but this information cannot automatically be combined to form an exact driver's or passenger's ear SPL response level with just a purely analytical SEA formulation. Fortunately, SEA is a flexible analysis framework that can implement measured transfer function data into the subsystem coupling by replacing the default analytically-calculated coupling between the dash surface and interior airspace subsystems with coupling factors determined by dash-surface-to-driver's-ear transfer functions. The development of a hybrid technique that uses measured transfer functions between points on the cabin side of the dash to the driver's ear will be presented as a novel approach to taking SEA prediction of energy transmitted through a dash for various configurations and using the measured transfer function data from inside the dash through the instrument panel to hybridize the SEA model into a predicted driver's ear SPL. The requirements, assumptions, advantages, and limitations to using this technique will be discussed. A proof-of-principle set of validation data with a corresponding SEA model and results making use of the transfer function measurements will be shown.

INTRODUCTION

At the very earliest stages of the vehicle development process, there is an important need for preliminary full-vehicle NVH predictions in response to proposed design concepts or changes. SEA, unlike FEA and BEA techniques, provides predictions that are very little affected by the exact details or by small variations of the geometry. SEA is thus very well-suited to supporting acoustical predictions when the geometry is uncertain or still evolving and can very quickly provide predictions of change in interior levels for proposed material, construction, packaging space, or compensatory sound package design changes for both airborne and structureborne excitation cases. [1] SEA can also be very useful to determine the main energy transmission paths of a system, especially when linked to a contribution analysis tool. As a vehicle program evolves and the details of the design become more finalized, predictions can be made to observe trade-offs between acoustic performance, cost, and weight and to find optimal solutions that meet defined objectives.

SEA is especially effective and is widely used as part of the vehicle design methodology for predicting the airborne noise transmitted through vehicle subassemblies such as the glasses, roof, door, and open sections of the floor. [2] A change in SPL inside the cabin from a change to the subassembly can be predicted with good accuracy. [3] An absolute prediction of a driver's or passenger's ear SPL level can nevertheless be difficult to establish. Difficulties can also arise when the propagation through the subassemblies is complicated by systems on the interior side of the passenger cabin that provide an additional amount of dissipation between the exterior to the open cabin interior. For subassemblies such as the dash, floor, and rear of the vehicle, the instrument panel, tunnel, console, rear seats, and package tray are systems that have an effect on the total noise transmitted and are not so easily modelled with a purely analytical SEA model. This weakness in modelling capability negatively impacts the ability to perform full-vehicle NVH predictions with a purely analytical model. Consequently, a lack of ability to properly characterize one of the main transmission paths makes it difficult to evaluate the relative contribution of each subassembly to the total interior vehicle SPL and hard to predict a total overall SPL.

This emphasizes the need to establish a hybrid method to combine SEA analysis with measured data in the context of an SEA model framework. The transmission paths that are too complex to be easily modelled, such as the instrument panel, console covering the tunnel, etc., can be replaced with SEA coupling factors based on measured transfer functions. Most of the time the acoustical parameters determined experimentally on a current vehicle provide a meaningful basis for the analysis of a next-generation vehicle's assembly groups. Transfer functions can be measured later on in the development process for the different available prototypes to complete the hybrid SEA model and to identify potential acoustical weaknesses.

The main challenge of this hybrid technique is to turn transfer functions, which provide implicitly all of the acoustical energy paths between two points, into SEA coupling loss factors, which characterize the power flow between subsystems that may or may not be physically connected. Implicitly, the use of transfer functions should provide indirect coupling. The goal of the present paper is not to provide relations between transfer function and coupling loss factors in a rigorous manner, but rather to point out that this technique is worthy of further consideration and feasible.

As a representative case, the direct noise transmission from the engine compartment through the dash subassembly and instrument panel to the driver's ear was chosen for study and presentation in this paper to illustrate the proposed technique. This path is an important source of total perceived noise at the driver's ear from engine noise and also presents an interesting test case since the dash can be modelled effectively using SEA but the instrument panel represents a further degree of complexity that is not so readily modelled using analytical techniques. Of further interest is that some sections of the dash (near the floor) can radiate somewhat directly into the passenger cabin while other sections of the dash are behind the instrument panel and noise passing through the dash in these locations is subject to a further degree of attenuation passing through the instrument panel into the passenger compartment. Because of these factors it is difficult to analytically predict the contribution through each section of the dash from the engine compartment to the driver's ear and so this is an interesting and useful test case for combining SEA analysis with measured transfer function data for NVH design predictions and transfer path analysis.

DEVELOPMENT OF SEA MODEL

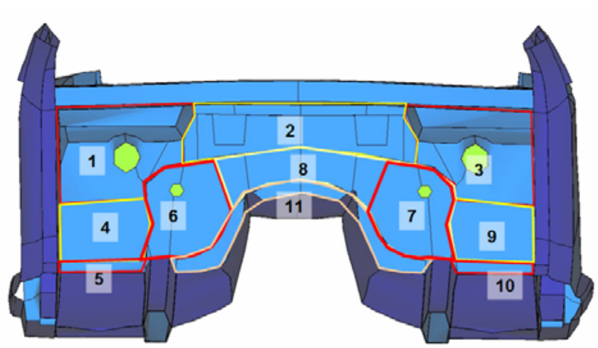

Figure 1 – Subdivision of Dash into 11 SEA Subsystems

An SEA model was developed to analytically predict the airborne transmission from the engine compartment through the dash, including all of the sound package layers and pass-throughs. The subdivision of the dash into 11 subsystems was based on each of the sections having either a substantially different excitation level on the engine side of the dash and / or a different sound package configuration from an adjacent dash subsystem. This justifies the definition of each separate SEA subsystem for each dash section and the SEA acoustic spaces on the engine compartment and passenger cabins side of the dash. Each layer of the sound package was modelled as an individual SEA subsystem as well, and the SEA model proved to be in good agreement with measured TL data for the trimmed dash with no instrument panel present. With the analytical part of the hybrid model completed, the next step of the process is to take measured transfer function data from the dash through the instrument panel to the driver's ear and to adapt these transfer functions into SEA coupling factors to be used in the SEA model so that the model can be used to calculate the total transmission through both dash and instrument panel.

TRANSFER FUNCTION MEASUREMENTS

A set of measured transfer functions were collected in a production, fully-trimmed vehicle by using a high-frequency volume velocity source at the driver's ear with microphones at the driver's and passenger's ears and at multiple locations within the instrument panel that could be feasibly instrumented. For thoroughness and to have an indication of the total transmission between the driver's ear and the engine compartment, 3 locations at the dash inside the engine compartment were also instrumented with microphones and recorded simultaneously with the other microphone locations.

Figure 2 – Representative Test Microphones behind Steering Column (left), Behind Instrument Cluster (center), and Below Steering Column and Near the Brake Pedal (right)

Summary of Acquired Data

The microphones were located from top to bottom and side to side, covering the entire surface of the dash. However, space and accessibility considerations made it significantly easier to instrument certain locations and much more difficult to get more than one microphone into other areas. The area behind the steering wheel and instrument cluster was particularly accessible and had enough space to allow for the placement of more microphones here than in other locations. The character of the data collected in this location (upper left part of the dash as viewed from the interior of the vehicle) is also very consistent and comprehensible. Because the character and consistency of this data is good and having multiple measurement locations provides a stronger foundation for comparison with a statistical analysis, this section of the dash and instrument panel, indicated as surface #1 in Figure 1 in the above SEA model description section, will be examined in more detail for the purpose of illustrating the hybrid technique and process.

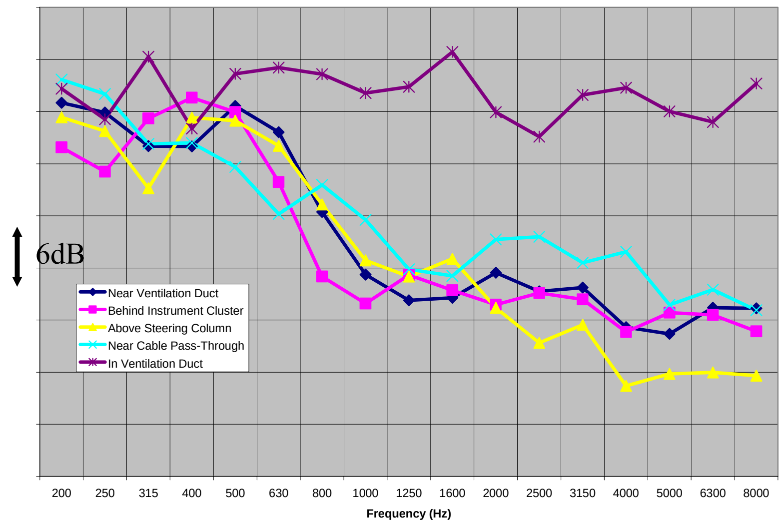

Figure 3 – Measured Transfer Functions from Driver Ear to Dash Section 1 (Covered by IP)

The transfer functions provide guidance as to the proper subdivision of the instrument panel SEA acoustic spaces. For transfer functions that have a similar character, a single SEA subsystem is judged to be adequate, while transfer functions with a significantly different character indicate that multiple SEA subsystems with different coupling factors should be used. In this example for surface #1 (upper left dash) as shown in Figure 1, the data from the point in the ventilation duct was excluded as being different in character due to the more direct path to the cabin. The other measurement points shown were averaged and used to characterize the transfer function to the SEA acoustic space subsystem between the dash and instrument panel for surface #1. Further subdivision of the subsystem can be used to account for the variance of the transfer functions at these different points if averaging between different points with highly-varying responses yields results of insufficient accuracy.

DERIVING COUPLING FACTORS FROM TRANSFER FUNCTIONS

SEA can serve as a useful hybrid framework to accommodate purely analytical predictions used together with information from measured transfer functions. In order to do this the analytically-determined coupling between subsystems should be replaced with coupling factors based on the measured data for the couplings in the framework that are to be specified from measured data. In this modelling example the couplings from the engine compartment through the dash and dash sound package components were calculated analytically with SEA as described above and it was determined to use the measured transfer functions from the cabin side of the dash (behind the instrument panel in most cases) to the driver's ear. This required the derivation of a set of coupling factors from the measured data that could be used in the model. Reciprocity will allow the use of the measured transfer functions from the driver's ear to the locations inside the instrument panel and the engine compartment under the actual operating conditions when the source at the driver's ear will actually be the receiver. SEA transfer functions derived using modal power must be reciprocal since coupling factors are reciprocal.

With the driver's ear location represented as an SEA acoustic space subsystem and the spaces inside the instrument panel on the passenger cabin side of the dash also represented as SEA acoustic space subsystems, a set of coupling factors between these spaces can be determined from the measured transfer functions. For the headspace subsystem h connected to a number i of SEA subsystems and for a dash acoustic space SEA subsystem j behind the instrument panel, then, by solving for a power balance and assuming that the modal power for subsystem i multiplied by the sum of coupling factors between h and i is negligible compared to the input power at subsystem h (from the volume velocity source), then [4, 5]:

$$\left[\beta_h + \sum_i \beta_{h;i}\right]\varphi_h = w_h^{in} + \sum_i \beta_{h;i}\varphi_i \qquad (1) \quad ; \qquad [\beta_j + \beta_{h;j}]\varphi_j = \beta_{h;j}\varphi_h \qquad (2)$$

where φ is the modal power, β is the SEA coupling factor, and W_{in} in the input power. The assumption that a dash subsystem j is not connected to other dash subsystems is used. Then the modal power at a dash acoustic space SEA subsystem is:

$$\varphi_j = \frac{\beta_{h;j}}{\beta_j + \beta_{h;j}}\left[\frac{w_h^{in}}{\beta_h + \sum_i \beta_{h;i}} + \frac{\sum_i \beta_{h;i}\varphi_i}{\beta_h + \sum_i \beta_{h;i}}\right] \cong \frac{\beta_{h;j}}{\beta_j + \beta_{h;j}}\frac{w_h^{in}}{\beta_h + \sum_i \beta_{h;i}} \qquad (3)$$

since the second term may be considered smaller than the first term. For a three-dimensional acoustic space, the SEA modal power and power input may be defined:

$$\varphi = \frac{\pi}{2}\frac{<p^2>}{R^a} \qquad (4) \qquad ; \qquad w_{in} = \frac{R^a}{\omega^2} < \ddot{q}^2 > \qquad (5)$$

where $<p^2>$ is the RMS sound pressure squared, R^a is the acoustic point resistance of the air in the acoustic space, ω is the angular frequency, and $<\ddot{q}^2>$ is the RMS volume acceleration squared at the source. Then equations (1), (4), and (5) yield:

$$\frac{\varphi_j}{w_h^{in}} = \left[\frac{\beta_{h;j}}{\beta_j + \beta_{h;j}}\right]\frac{1}{\beta_h + \sum_i \beta_{h;i}} = \frac{\pi}{2}\frac{\omega^2}{R_h^a R_j^a}\left|\frac{p_j}{\ddot{q}_h}\right|^2 \qquad (6)$$

and it can be seen that the quantity $\left|\frac{p_j}{\ddot{q}_h}\right|$ is one of the measured transfer functions belonging to the set of measured data of which some are shown in Figure 3. Then the definitions of the acoustic point resistance of a three-dimensional space and the effective head space h loss factor can be used:

$$R^a = \frac{\rho c k^2}{4\pi} \quad (7) \qquad ; \qquad \beta_{eff} = \frac{2.2}{\pi}\frac{\omega^2}{c_a^3}\frac{V}{T_{60}} = \beta_h + \sum_i \beta_{h;i} \quad (8)$$

where rho, c, and k are the density, speed of sound, and wavenumber of air, respectively, V is the volume of the air space, and T60 is the measured reverberation time. Equations (7) and (8) can be used with equation (6) to obtain:

$$\left[\frac{\beta_{h;j}}{\beta_j + \beta_{h;j}}\right] = 8\pi^2 \frac{2.2}{\rho_a^2 c_a}\frac{V}{T_{60}}\left|\frac{p_j}{\ddot{q}_h}\right|^2 \quad (9)$$

The SEA coupling factor is then determined based on a measured transfer function, subsystem loss factor, cabin volume and reverberation time, and properties of the air. A loss factor β_j is calculated from the assumed or measured absorption in subsystem j and then a corresponding coupling factor $\beta_{h;j}$ is calculated and applied.

Comparison of Hybrid Predictions to Measured Data

Applying this formula to the measured transfer functions yields a set of coupling factors that can be applied to the SEA modelling framework. Figure 4 indicates the transfer function predicted by the SEA hybrid model between the driver's ear and the dash section #1 behind the instrument panel compared to the measured transfer function. To go one step further, with the complete set of coupling factors calculated and applied to the model and used in conjunction with the predictive analytical SEA model through the dash, a predicted transfer function from the driver's ear to the engine compartment based on both the derived coupling factor and predictive SEA model compares favorably to the corresponding measurement (shown in Figure 5).

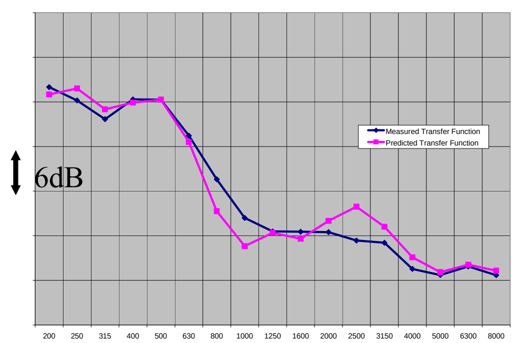

Figure 4 – Measured vs. Predicted Transfer Functions from Driver Ear to Dash Section 1

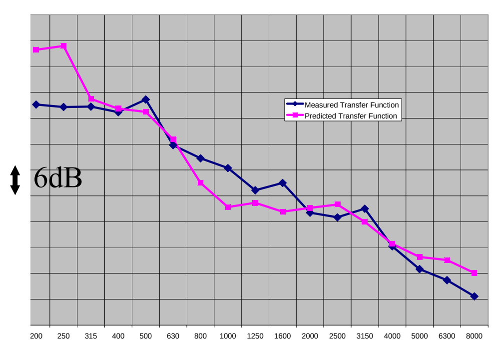

Figure 5 - Measured vs. Predicted Transfer Functions from Driver Ear to Engine Comp.

CONCLUSIONS

It is to be noted that the hybridization of the experimental techniques with the SEA or power flow methods in general is currently remains a challenge. The use of the transfer functions combined with SEA modeling for airborne noise issues is actually the generalization of a previously-developed technique for structures. A method has been developed and validated for structureborne noise modeling for one- and two-dimensional structures with hybrid models based on measured point mobilities with particularly relevant application to the mid-frequency range (100 to 1000 Hz). [6]

This proposed airborne hybrid technique still has issues to be addressed concerning practicality (positioning of the microphones in confined places, small monopole source assumptions, etc.,) and is subject theoretically to a certain number of restrictive assumptions. The main goals of this technique are to have the possibility to include complex structures that can't be easily modeled as "black box" components in an analytical framework, and to allow for better spatial resolution of the interior predictions using SEA and to better differentiate between points within the cabin.

The next logical step will be to see if reciprocity holds and that with a typical excitation case (here in the engine compartment) a predictive model using these measurement-derived coupling factors can adequately predict the target response (driver's ear SPL) using the SEA coupling factors derived from the measurements.

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