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Virtual Powertrain Swap in Vehicle Development Utilizing a Time-Domain Source-Path-Receiver Model

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ABSTRACT

A test and signal processing strategy was developed to allow a vehicle OEM to predict the sound quality of a new powertrain in an existing vehicle. The approach leveraged time-domain Source-Path-Contribution (SPC) techniques to build an experimental breakdown of an existing vehicle with a baseline powertrain configuration (V8 engine). The alternate powertrain (V6) was characterized in a different vehicle and its acoustic source strength and forces estimated by means of matrix inversion approach. The source strength and forces of the new engine were inserted into the original vehicle model to predict the acoustic signature, in time, at the driver's ears. The approach was validated by comparing the prediction to data measured with the new powertrain in place. The experimental and model building procedure were then optimized and adopted as standard procedure to aid vehicle development programs.

1. INTRODUCTION

A vehicle OEM was investigating new methodologies to support NVH related vehicle activities earlier in the vehicle development phase. One desire was to have the ability to virtually install a new powertrain into an existing vehicle and predict the structural and acoustic responses, which would allow for an early assessment of performance relative to vehicle-level targets and identify any key areas of concern before the availability of mule vehicles. Utilization of a source-path-contribution (SPC) model would not only accomplish these goals, but also allow for an estimation of contributions from individual acoustic and structural sources.

2. TECHNICAL APPROACH

A time-domain SPC model utilizes a source-path-receiver approach to predict forces and source-strengths generated at each source, and provides an understanding of the sensitivity of the individual paths between the sources and the receiver positions. These items, in combination, are then used to predict both the vibration and acoustic responses at the response locations, which are typically the customer interface locations. The time-domain nature of the model additionally provides the ability for playback of both the individual contributions from each source as well as the sum of all contributions for the purposes of performing listening studies, jury evaluations, and additional data analysis.

SPC enables the engineer to understand how sound and vibration are transmitted through both acoustic and structure-borne paths. There are two conventional techniques utilized for estimating structure-borne forces acting on the body at the attachment points of a source, the impedance matrix method and the mount stiffness method. Regardless of method used, the partial contribution of each path is calculated by multiplying the calculated force by the measured body sensitivity function. The types of errors encountered are typically due to lack of reciprocity and includes: cross-axial sensitivity of transducers causing false responses in out of plane directions, signal-to-noise problems where a response point is partially isolated from the excitation point, and difficult control of impact hammer excitation [1].

The goal of this development was to virtually install a new powertrain into an existing vehicle platform and assess the noise and vibration responses. The steps utilized for these efforts are described below:

1. Establish acoustic and structural sources
2. Characterization of the individual sources (force or source strength)
3. Characterization of individual vehicle paths
4. Calculation of contributions
5. Characterization of alternate powertrain system
6. Calculation of contributions from alternate powertrain system

3. POWERTRAIN SOURCE CHARACTERIZATION

One of the initial steps for the project was to establish the components and systems within the vehicle that would be considered acoustic and structural sources, and likewise which paths would be considered. The surrogate vehicle used for this development was a unibody sport-utility-vehicle, and the primary acoustic and structural sources were the engine and transmission. Additionally the exhaust system, intake system, and tires were established as structural/acoustic sources.

A. Acoustic Sources

Acoustic sources for this investigation included several sources surrounding the engine and transmission, intake system, exhaust system, and tires for a total of 18 acoustic sources. Microphones were placed near to the center of each of the 18 acoustic sources as well as at several indicator positions. Operational data was collected for multiple vehicle events, including both steady-state and transient events. The operational data, in combination with the vehicle path data (to be discussed later in this paper) can be used to calculate the acoustic source strengths (Q) for each source per the following:

$$\begin{Bmatrix} Q_1 \\ \dots \\ Q_n \end{Bmatrix} = \begin{bmatrix} \frac{P_{11}}{Q_1} & \cdots & \frac{P_{1n}}{Q_n} \\ \vdots & \ddots & \vdots \\ \frac{P_{m1}}{Q_1} & \cdots & \frac{P_{mn}}{Q_n} \end{bmatrix}^{-1} \begin{Bmatrix} p_1 \\ \dots \\ p_m \end{Bmatrix} \tag{1}$$

B. Structural Sources

Structural sources included in this investigation included the powertrain mounts, transmission mount, exhaust hangers, and tires for a total of 9 structural sources. Accelerometers were placed at each of the 9 source locations, as well as at multiple indicator positions. Operational data was collected for both steady-state and transient events, and two methods (impedance matrix and mount stiffness) were evaluated for calculation of the forces.

1. Impedance Matrix Method

The Impedance Matrix method of force approximation estimates the forces from measurements of operating accelerations and artificial excitation measurements, noted in the equation below:

$$\begin{Bmatrix} f_1 \\ \cdots \\ f_n \end{Bmatrix} = \begin{bmatrix} \frac{\ddot{X}_{11}}{F_1} & \cdots & \frac{\ddot{X}_{1n}}{F_n} \\ \vdots & \ddots & \vdots \\ \frac{\ddot{X}_{m1}}{F_1} & \cdots & \frac{\ddot{X}_{mn}}{F_n} \end{bmatrix}^{-1} \begin{Bmatrix} \ddot{x}_1 \\ \cdots \\ \ddot{x}_m \end{Bmatrix} \tag{2}$$

This method can typically provide very good estimates of the input forces, and can provide significant feedback to be able to assess reciprocity within the data and identify potentially bad measurement points that could affect the force approximations.

2. Mount Stiffness Method

This method of force approximation estimates the forces from measurements of the operating accelerations across the active and passive sides of a rubber mount, and multiplying by the dynamic stiffness of the mount, as noted below.

$$f = K^*\Delta X \tag{3}$$

Where K* is the dynamic stiffness, and ΔX is the displacement across the mount (defined below).

$$\Delta X(t) = \iint \left(X_A(\ddot{t}) - X_P\ddot{(}t)\right) dt \tag{4}$$

One of biggest drawbacks to this method is the necessity and reliance on accurately assessing the dynamic stiffness of the mounts in question. This generally requires the mount to be removed from the vehicle to be evaluated. Difficulties can often exist for providing the necessary fixtures to adequately measure the stiffness, as well as determining the appropriate input loads for measurement. When installed into a vehicle, a mount will be imparted with many different static and dynamic loads, at many different frequencies. Each of these variable can have a significant effect on the stiffness for a rubber mount.

If it is not possible or efficient to remove the mounts from the vehicle and measure the dynamic stiffness, it is possible to estimate the dynamic stiffness utilizing SPC-based tools. This can be accomplished by using the operating force estimations from the matrix inversion method, along with the operating accelerations across the active and passive sides of the mount from the mount stiffness method to solve for K*.

$$K^* = \frac{f_{matrix\ inversion}}{\Delta X_{mount\ stiffness}} \tag{5}$$

The dynamic stiffness of the mount can then be manipulated within the SPC software to determine the vehicle-level effects due to proposed changes to the mount stiffness.

Describe methods? Peak hold, order concatenation, etc.

4. VEHICLE PATH CHARACTERIZATION

The structural vehicle path characterization for this development was accomplished through the use of modal hammer impact data, however a shaker excitation would likely have been equally sufficient. For these tests the modal hammer provided the calibrated force input to the system at each of the structural sources and the responses were monitored both at the receiver positions inside the vehicle and at each source and indicator accelerometer position to establish both the local and global transfer function matrix. The matrix was used in combination with the operating vibration to calculate the forces at each source location as described above in equation 2.

The acoustic transfer functions were measured in a similar fashion using a volume velocity source and monitoring the acoustic responses at all of the microphone positions. Source strengths were calculated per equation 1. Note that the volume velocity source for acoustic transfer functions is analogous to the impact hammer for structural transfer functions. The volume velocity source uses a pair of phase-matched microphones at the opening of the output, this is then used to determine the volume velocity-to-sound pressure transfer functions.

5. SPC MODEL DEVELOPMENT

The source-path-contribution (SPC) model was established within the analysis software to include both the acoustic and structural sources. The model was configured to utilize time-domain data sets, which provided the ability to utilize not only steady state frequency domain data, but also transient run-up and coast-down data sets. This also allowed for calculation of acoustic and structural source strengths (Q, f) in the time domain which were used to calculate time domain contributions at the receiver locations, including the driver ear microphones and seat/steering wheel responses per the equations below.

$$\begin{Bmatrix} f_1 \\ \cdots \\ f_n \end{Bmatrix} \begin{Bmatrix} \frac{P}{F}_1 & \cdots & \frac{P}{F}_n \end{Bmatrix} = \begin{Bmatrix} p_1 \\ \cdots \\ p_n \end{Bmatrix}_{SB} \tag{6}$$

$$\begin{Bmatrix} Q_1 \\ \cdots \\ Q_n \end{Bmatrix} \begin{Bmatrix} \frac{P}{Q}_1 & \cdots & \frac{P}{Q}_n \end{Bmatrix} = \begin{Bmatrix} p_1 \\ \cdots \\ p_n \end{Bmatrix}_{AB} \tag{7}$$

The total predicted sound pressure levels at the receiver positions is then a summation of all of the contributions, both structure-borne and airborne.

6. COMPARISON OF PREDICTED AND ACTUAL

For validation of the SPC model it was possible to compare the total sum of contributions to the actual measured acoustic responses. This comparison provides confirmation that the structure-borne and acoustic sources utilized in the model were sufficient in accurately characterizing the vehicle. Significant deviations between the sum of the contributions and the measured signal in an SPC model could indicate that key acoustic and/or structural sources were not included in the model, or potentially not characterized properly. This could occur if the microphones and/or accelerometers were not placed in the optimal locations or if too few transducers were utilized to accurately characterize the source strengths and forces.

For this development, both steady-state and transient run-up data sets were used to validate the SPC model. Results for each of these conditions are noted in Figure 1 and Figure 2. The results indicate that the characterization of the sources and the paths were sufficient to estimate the contributions inside the vehicle. The SPC model utilized was in the time-domain, so it was also possible to conduct subjective listening studies between the measured sound and the sum of the contributions. Based upon these evaluations it was determined that the SPC model provided results that accurately characterized the key acoustic features of the vehicle.

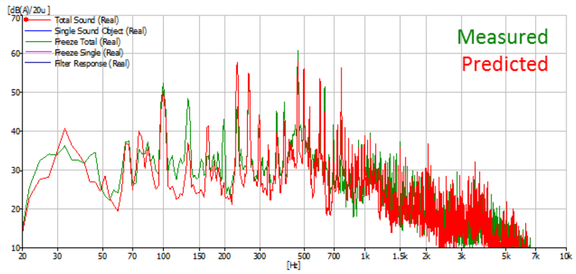
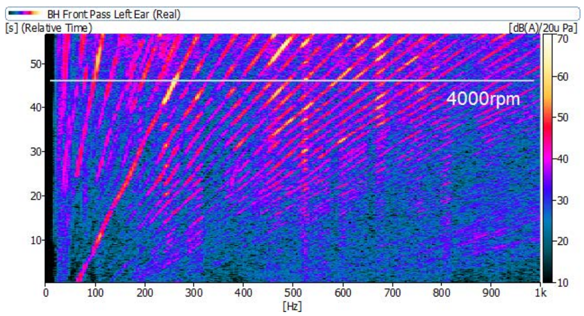
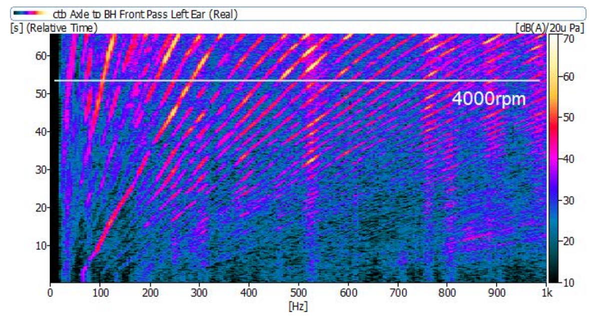


Figure 1: Steady State SPC Validation



Measured Acoustic Response



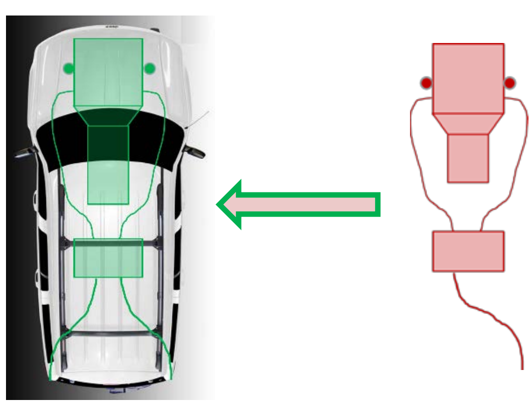
Predicted Acoustic Responses

Figure 2: Transient Run-up SPC Validation

7. SECOND POWERTRAIN SOURCE CHARACTERIZATION

The original powertrain characterized was a V8 engine and mating transmission. One goal of this development was to virtually install a secondary powertrain and predict the noise and vibration responses inside the vehicle for comparison to the original powertrain and for assessment against proposed vehicle targets. Once the SPC model was established with the original powertrain, all that was needed was the structural and acoustic characteristics of the second powertrain. This was accomplished in a similar fashion as the original powertrain, but in a different vehicle. This characterization could have as easily been conducted outside of a vehicle on a powertrain dynamometer if the powertrain was still in development and access to a vehicle was not available. Furthermore, if full hardware was not yet available, the data could have also been provided through analytical predictions of acoustic radiation and structural inputs.

The exhaust system for the secondary powertrain was significantly different from the original, so characterization of this system was also necessary for both the structural and acoustic inputs into the vehicle.



V8 Powertrain Configuration V6 Powertrain Configuration

Figure 3: Powertrain Configuration Comparison

8. PREDICTION OF NEW POWERTRAIN IN ORIGINAL VEHICLE

Upon establishing acoustic and structural characterization of the second powertrain system it was possible to utilize these forces and source strengths in combination with the path terms for the vehicle. The result of this analysis provides the calculated contributions to the vehicle interior for the secondary powertrain virtually installed into the original vehicle.

The local transfer functions (vehicle path terms) were utilized in combination with the measured V6 powertrain acoustic and structural characterization to estimate the source strengths (Q, f). These source strengths were then combined with the global vehicle transfer functions to calculate the structure-borne and airborne contributions at the receiver locations.

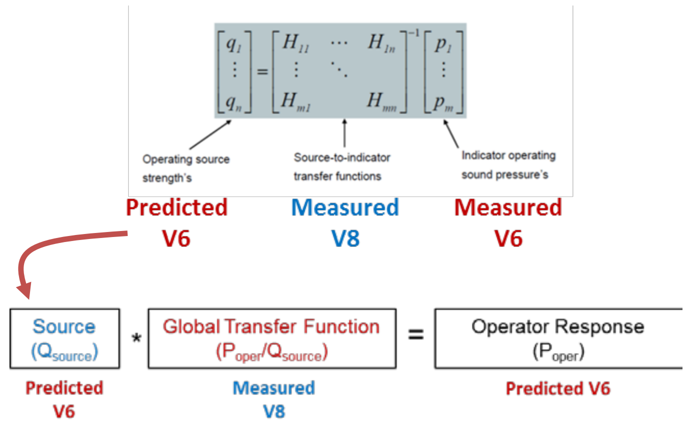


Figure 4: Process to Virtually Install New Powertrain

The results of these calculations are noted below in Figure 5 and Figure 6, and highlight various frequency ranges in which the secondary (V6) powertrain is expected to produce a different experience to the customer as compared to the baseline powertrain (V8). This information can be utilized to identify potential development activities if vehicle-level targets are not achieved with the secondary powertrain. The individual contributions from each of the structural and acoustic sources can be interrogated further to identify which components or systems are the primary contributors to any undesired sounds. Alternate design iterations can also be evaluated within the SPC model to validate proposed design changes prior to the availability of hardware (new muffler tuning, etc.).

The time-domain nature of the SPC model was again utilized to conduct listening studies to evaluate the performance of the secondary powertrain. Subjectively the character of the sound was significantly different, and several sound quality metrics were calculated on the time signal to objectively characterize the differences.

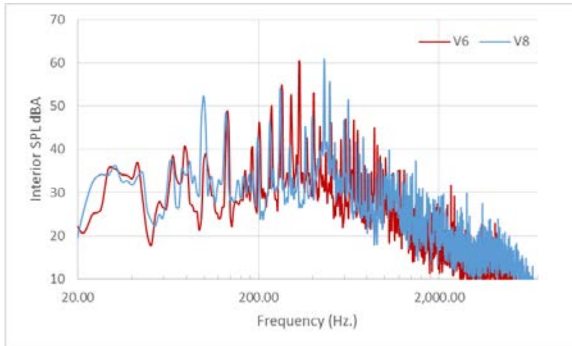
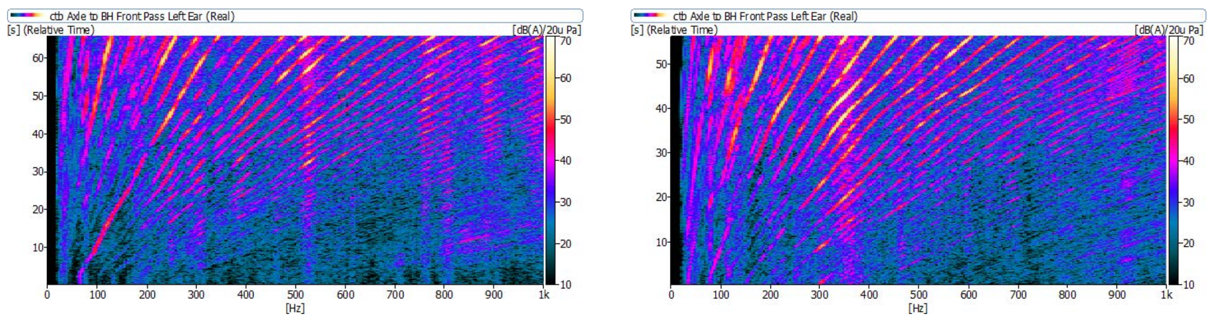


Figure 5: Steady State Contributions of New Powertrain



V8 Powertrain V6 Powertrain Virtually Installed into Vehicle

Figure 6: Run-up Contributions of New Powertrain

9. METHOD UTILIZATION

The methods described in this paper have several applications in the vehicle development process for both OEMs and suppliers, and can allow for up-front predictions of NVH performance prior to the availability of costly prototype vehicles. These methods, primarily developed to evaluate the NVH performance of new powertrains in existing platforms, can also be used for target setting at system, subsystem and component levels. This can prevent late changes to a program due to high noise levels and reduced subsequent costs. As part of a target setting process, this method can quantify competitive performance for both powertrain noise and vibration and vehicle sensitivity.

One example of this is for the evaluation of a new powertrain as installed into an existing vehicle platform. In this case the vehicle-side path terms of the SPC model are known, while the powertrain source information can be either measured or predicted without the need for installing the system into an actual vehicle. A similar example is for the evaluation of an existing powertrain to be installed into a new vehicle platform. For this case the powertrain source information is known, while the vehicle-side path terms can either be measured or predicted from analytical data.

In either case, the SPC methodology can improve the engineering decision process and allows parallel evaluation of design alternatives and product variants, throughout the vehicle development process. This upfront activity can help management make quick and accurate powertrain and driveline selections. This methodology also provides a greater understanding of the total predicted NVH performance, which allows for assessment against vehicle-level targets as well as the ability to perform subjective listening studies due to the time-domain capabilities of the model, which allow for inclusion of transient and impulsive events.

This process additionally provides feedback into the key sources and paths in support of any issues identified during the target assessment and/or subjective listening studies. For these 'problem' areas, changes to either the sources (forcing functions) or the paths (vehicle-side attachment point stiffness', etc.) can be evaluated within the SPC model without the need for physical testing and hardware evaluations. This can aid in target setting for new development activities for both the powertrain source inputs as well as the vehicle-side responses, and places a greater emphasis on test-based models as opposed to the reliance of solely hardware evaluations and troubleshooting efforts later in the vehicle development cycle.

REFERENCES

1. Moller, N., & Batel, M. (2005). Obtaining Maximum Value from Source/Path Contribution Analysis. *SAE Technical Paper 2005-01-4183*.
2. Pietila, G., et all (2010). Noise and Sound Quality Optimization of Agricultural Machine Cab. *SAE Technical Paper 2010-10-05*.