2009-01-2091

Noise Path Analysis Process Evaluation of Automotive Shock Absorber Transient Noise

David Bogema
Bruel & Kjaer

Paul Goodes
Sound Answers, Inc.

Chahe Apelian and Michael Csakan
Hyundai Kia American Technical Center Inc.

ABSTRACT

Shock absorber transient noise, often referred to as "chuckle" or "loose lumber", has been a vehicle level noise and vibration concern for many years. The noise often occurs with lightly damped shock tuning under small road inputs at low speed. This transient type noise is of particular concern to the operator because it can sound like mechanical looseness in the chassis.

This noise concern is generally addressed late in the design cycle and the options of a fix are limited to a change in damper tuning or added mass. A need for a wider design envelope exists to address this concern which must include noise paths into the structure and body sensitivity.

The study documented in this paper walks through the process of acquiring this noise on the road and reproducing it in the lab on a 4-post hydraulic test rig. The noise path analysis process is then evaluated in detail for this transient type of noise to compare the results of acquiring the NPA data as a fully disconnected suspension, fully connected suspension and a reduced 3-point shock attachment. The study then evaluates the fully disconnected suspension method for a square matrix compared to an over-defined matrix. Finally a comparison of frequency versus time domain noise path analysis is performed.

INTRODUCTION

The analysis and correction for shock absorber transient noise has been addressed from several different directions. Shock absorber tuning can be adjusted to minimize the noise. Investigations have been performed to model the internal valving components and operation during reversals. Modifications are also made to the suspension system to add weight or passive damping in order to reduce the response of the vehicle at the shock attachment points. Each of these approaches has shown to make effective improvements for the vehicle level performance but each has drawbacks.

In order to broaden the design envelope to address this issue, investigation into suspension and body sensitivity is explored. The purpose of this study was to evaluate the vehicle for sensitivity to this noise beyond the shock absorber.

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. This process requires a minimum of three (3) reviews by industry experts.

ISSN 0148-7191

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Printed in USA

SAE International™

The appropriate vehicle data on the road was recorded and then replicated on a 4-post hydraulic road simulator in the lab. Noise path analysis was then performed on one corner of the vehicle where the noise was most prominent. The noise path analysis process was evaluated to compare the technique with a fully disconnected suspension, fully connected suspension and a reduced 3-point shock attachment NPA model. The study then evaluates the fully disconnected suspension method for a square matrix compared to an over-defined matrix. Finally a comparison of frequency versus time domain noise path analysis is performed for this transient noise event.

PROBLEM DEFINITION

The transient noise occurring in this vehicle was the classic "loose lumber" or "chuckle" noise. This is a transient type of noise related to a low amplitude (+/- 5 mm) suspension input of 10-15 Hz. The noise usually occurs at a low vehicle speed (less then 20mph) on a rough surface such as grass, spalled concrete or a dirt road. This input causes a transient force to be generated in the suspension system with broad frequency content (200-1000 Hz). The vehicle responds to this frequency input and the result is a "loose lumber" noise.

IN-LAB EXCITATION

Vibration data was taken on the road for replication on a 4-post test machine in the lab. Accelerometers were placed at each corner of the vehicle, on the wheel ends and the shock absorber piston rods. The data from the wheel ends was then used with time domain RPC (remote parameter control) to rebuild the road on a 4-post test machine. The data from the shock absorber piston rods was used to help evaluate the accuracy of the road reproduction.

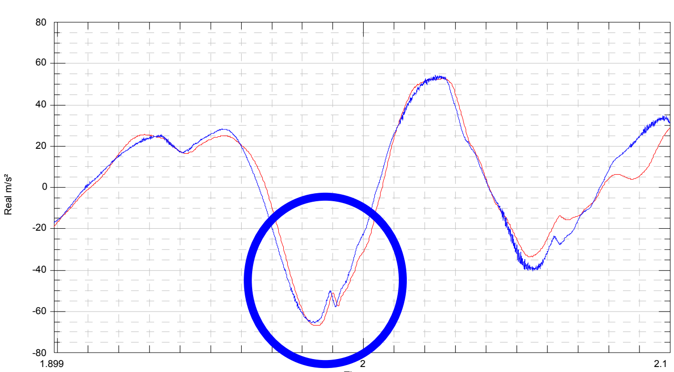

Figure 1 – Wheel end comparison

The data shown in figure 1 is a comparison between the wheel end vibration data on the road and on the 4-post test machine. The area of focus for this noise is just after a reversal in motion of the shock absorber. The small discontinuity shown after the reversal is the reaction to the force input which causes the objectionable noise.

Comparison of the output was then performed in the time and frequency domains to ensure the correct noise was replicated. Figure 2 shows a time domain comparison of the shock absorber piston rod acceleration between the road and the 4-post tester.

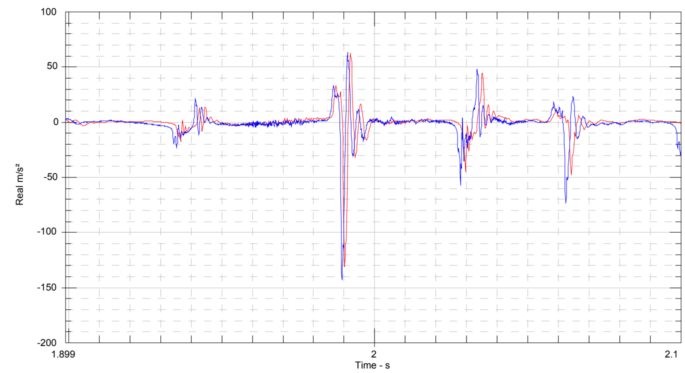

Figure 2 – Piston rod comparison (time)

The response data for the shock absorber piston rod shows that replication on the 4-post is an accurate representation of this noise. During the iteration process the RPC software has statistical tools available for evaluating the accuracy of the reproduction. For this type of transient noise it is important to focus on the replication and response comparisons to a few critical noise events rather then the entire time series.

SOURCE & PATH IDENTIFICATION

A source-path-contribution analysis was performed to understand the primary noise paths of the sound from the shock absorber into the vehicle.

As part of this analysis, several configurations were used to explore and document the effects of measuring transfer path functions with the suspension connected versus disconnecting the paths for the measurements. Also, a reduced 3-connection-point measurement was performed in addition to a larger multi-point measurement.

Both a frequency-domain analysis and a time-domain analysis were performed. Most of the analysis was performed with frequency-domain data. This is notable in that this is a short transient signal. Many source-path-contribution analyses that have been previously presented focus on stationary signals or longer time-varying signals such as engine run-ups which are easily characterized in the frequency or order domain.

SPC WORKFLOW – The workflow when performing any source-path-contribution analysis is a very important part in achieving successful results. The workflow utilized in this analysis is included in Figure 3.

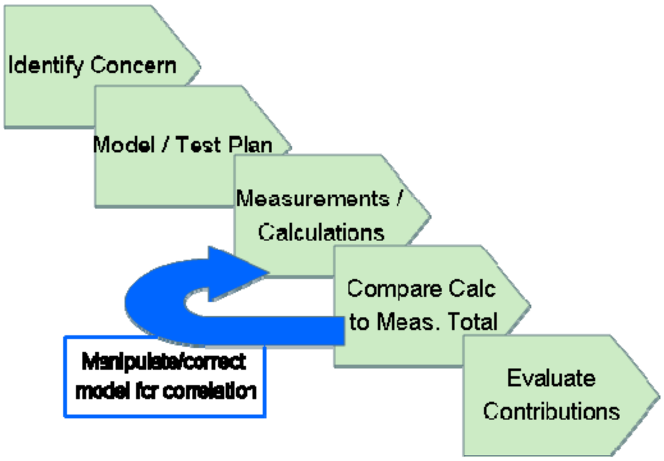

Figure 3 - SPC Workflow

The very first step, "Identify concern" is perhaps the most important of all the steps. This includes not only the particular sound that is being investigated, but also the frequency range of the sound and any other identifying characteristics. This is important in limiting the scope of the investigation to only the phenomena and frequency range of interest.

In this case, the particular event of interest has been defined and described in the previous sections. For the SPC analysis, a single transient event is used for the analysis.

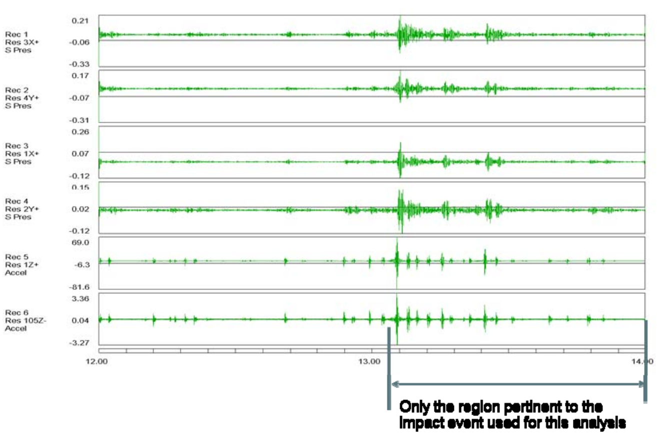

Figure 4 - Transient Event

The transient event is approximately .95 seconds long. The transient event was transformed from the time domain, first as a single FFT performed over the .95 seconds, then as a peak-hold FFT performed using 400 lines with a 3.2kHz span (with a resulting frame length of .125s), with 95% overlap which provided 131 frames of data over the .95 seconds. The peak-hold method shows similar characteristics to the single-FFT method, and the graph is much cleaner and easier to read.

Figure shows the comparison between the two methods – the blue traces are the single FFT, the green/red traces show the peak-hold amplitude and phase. Based on this result, the peak-hold method was used for the remainder of the data processing.

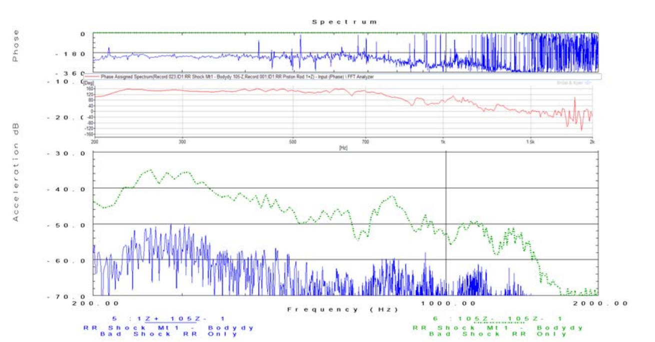

Figure 5 - FFT of Transient Signal

The final step in identifying the concern was to determine what frequency range or ranges were important.

To do this, the response spectrum of the accelerometer at the top of the shock absorber for the "bad shock" (the shock absorber used for all the testing for this SPC portion of the study) was compared to the spectrum of a "good shock", a shock absorber which did not cause the "loose lumber" noise. Figure shows the key regions of difference in the levels of response for loose lumber noise are 250-500Hz, 525-650Hz, and 700-1000Hz.

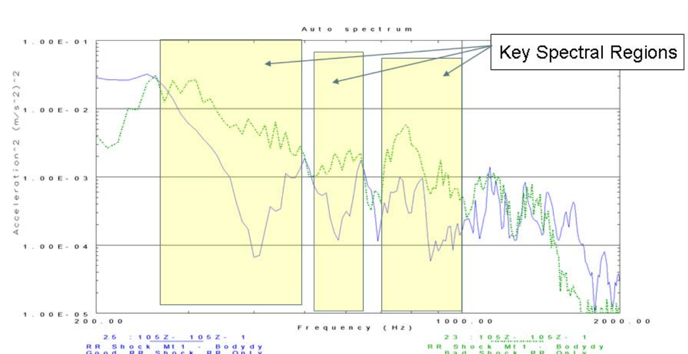

Figure 6 - Frequency Ranges of Interest

SPC MODEL/TEST PLAN – Once the specific concern has been identified thoroughly, the test plan and model can be defined.

To simplify the source path contribution analysis, the excitation was limited to only the right rear corner of the vehicle, using input on a 4-post hydraulic road simulator as described previously.

There were 4 microphones placed in the vehicle at various locations. For simplicity of presentation, the results are limited to the use of a single microphone, the right rear corner microphone which is the closest microphone to the excitation source, located near the headrest of the right rear passenger.

A matrix impedance method source-path-contribution approach was used. This requires P/F (sound pressure / input force) transfer functions between each attachment point and the response microphone, as well as A/F (acceleration / input force) transfer functions between all the accelerometer locations on the structure.

It is typically desirable to disconnect the structure at the attachment points before measuring the transfer functions. However, this is often time consuming. Here, both the connected and disconnected conditions were used and compared.

Another consideration is that for the matrix-impedance method, the matrix is often over-determined to increase the quality of the matrix inversion and the final results. Here both the square matrix (accelerometer responses only at connection points) as well as a non-square over-determined matrix (extra accelerometer responses) are used.

In summary, the configurations analyzed were as follows:

1. Simple 3-point SPC analysis, using 2 shock-top attachment points and 1 shock-bottom attachment point (on wheel hub) as paths
    a. All P/F and A/F measured in "disconnected" condition. Shock removed from vehicle, but body side bracket retained. An overdefined matrix was used for this analysis. (18X9)
2. Full Rear Suspension/subframe attachment points
    a. "Disconnected" P/F and A/F functions
        i. Overdefined Matrix (42 X 24)
        ii. Square Matrix (24 X 24)

    b. "Connected" P/F and A/F functions, where all FRFs were measured with alll attachment points connected, in-situ
        i. Overdefined Matrix (42 X 24)

TRANSFER FUNCTION MEASUREMENTS – Two sets of transfer functions where measured, using an impact hammer.

1. All transfer functions were measured with all points in their standard, connected configuration.
2. All transfer functions measured with mounting points were disconnected.

Ideally, when using any SPC method, the P/Fs and A/Fs should be measured with the paths disconnected at the point of the source joining the path (in this case, where the shock attaches to the body, or where the subframe attaches to the body). It is however faster and easier, and therefore potentially desirable, to measure these functions with the paths connected, but this tends to produce incorrect results. The results of the "connected" and "disconnected" measurement methods are compared here.

SPC PROCESSING

<u>Full Disconnect –</u> The Full-Disconnect condition is the first condition to be examined. The paths here included the subframe attachment points, shock attachment and trailing arm connection.

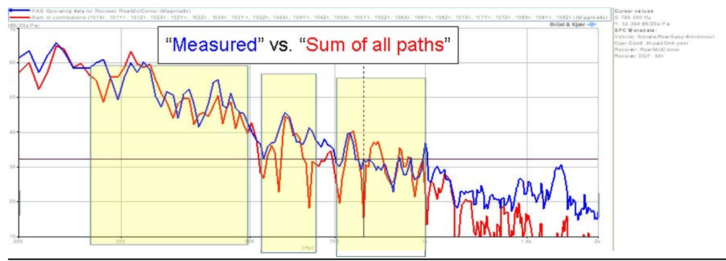

Figure 7 - Full Disconnect Measured vs. Sum of All Paths

Figure shows that the sum of the 24 paths matches well with the measured response at the interior microphone at the peaks.

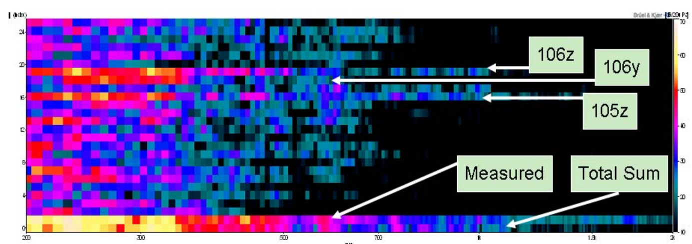

Figure 8 - Full Disconnect Path Contributions

In Figure 8, the path contributions are shown as a 3-d color map. Here the main contributions are from 106z, 106y and 105z, which are the shock top attachment points. Figure shows that the sum of only the shock top paths accounts for nearly all the content measured at the interior microphone, and is quite similar to the "sum of all paths" shown in Figure 7.

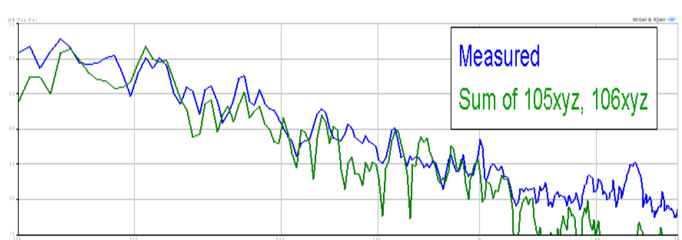

Figure 9 - Full Disconnect, Sum of Shock Top Paths Only

3-point Shock Attachment – As a reduced measurement set, the 3-point shock attachment set was analyzed. This measurement set reduces the number of paths from 24 to 9, thus reducing the error that may be entered into the calculations. Figure 10 shows that, again, the shock paths when summed together account for the majority of the sound at the interior of the vehicle.

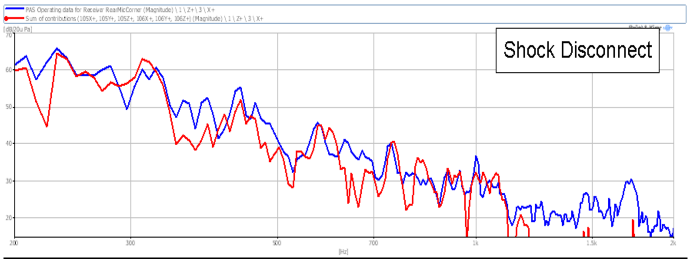

Figure 10 - 3-Point Shock Attachement - Total Measured (Blue) vs. Sum of Shock Top Contribution Paths (Red)

Connected – In this analysis, the FRF matrix between connection points and the FRFs measured from the connection points to the interior microphone were measured with the subframe and all connection points fully connected. This yielded inferior results compared to the "disconnected" case shown previously, but the results were generally correct. Figure 11 shows that the "sum of all paths" measurement does come close to the "measured" data, but when compared with the "disconnected matrix" data in Figure 7, it is obvious that the results here for the "connected matrix" are inferior.

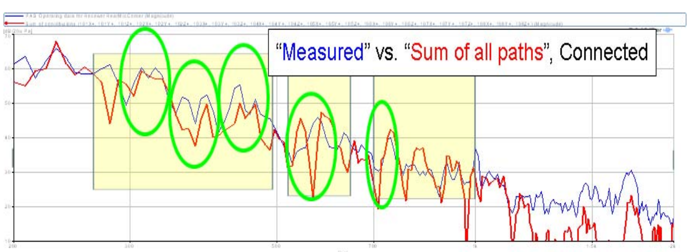

Figure 11 - "Connected" Measured vs. Sum of All Paths

Often it is desired to bypass the sometimes time-consuming step of disconnecting the structure at the connection points in order to make transfer function measurements to the interior and between connection points. This is sometimes acceptable, depending on the purpose of the analysis being done. It will involve some added error, but will often give results that are generally correct. So, for example, when performing very fast trouble-shooting where speed is of the essence, leaving the connection points connected may be permissible and yield acceptable results. When performing detailed analysis for target setting, correlation or some other task where accuracy is very important, the "disconnected" method should be used.

Square vs. Overdefined – In this case, the square matrix is compared to using an overdefined matrix. Up to this point, only the overdefined matrices have been used.

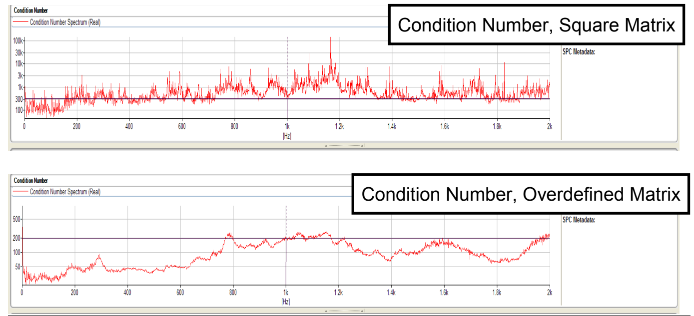

Figure 12 - Condition Number - Square and Over-Defined

Figure 12 shows the condition number of the two matrices. The condition number indicates the robustness of the matrix, or the relative amount of useful to un-useful data in the matrix. A lower condition number is better. The square matrix has a much higher condition number. Even though a threshold value is applied to the matrix singular values based on the condition number in order to better condition the matrix, this is still an indication of the quality of the matrix.

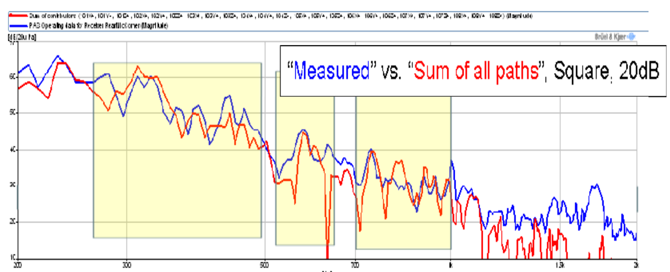

Figure 13 - Measured vs. Sum of All Paths, Square Matrix

In this case, as shown in Figure 13, the square matrix still gives a very good answer, and very similar to that of the over-defined matrix shown in Figure 7. So, in this case, the argument for using an over-defined matrix is not strong. This is probably due to the fact that most of the energy of the shock absorber transient is travelling up through the shock top connections. Also, as mentioned previously, a singular value threshold was used when processing the matrix, which helped improve the results markedly.

Frequency vs. Time domain – In addition to the frequency-domain analysis, a similar analysis was performed in the time-domain for the 3-point shock attachment configuration. In this case, the FRF matrix was inverted in the same manner as in the frequency-domain approach, but then the resulting inverted matrix was used as an FIR filter set and applied to the time histories of the source data. The result was the same as that of the frequency domain analysis, but with the added ability to listen to the result. From this, it was audibly obvious that the "sum of top shock paths" was responsible for the loose-lumbar noise, and that the other paths were not important in creating this noise.

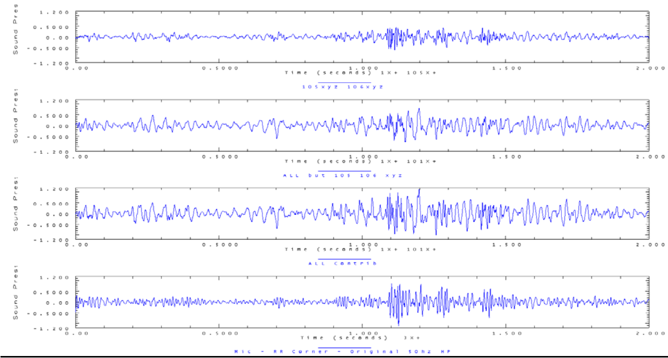

Figure 14 - Time-domain SPC Results

CONCLUSION

The "loose lumber" noise can be identified as several frequencies and a general high level of noise in the 250-1000Hz region

The primary path for the "loose lumber" noise is through the shock top mount points.

The "Subframe disconnect – full overdefined matrix" condition provides good correlation to the measured interior data

The "Shock disconnect" simplified model (3 connection points) provided similar results to the "Subframe disconnect – full overdefined matrix".

The "Subframe connected – full overdefined matrix" condition yielded similar results to the "Subframe disconnect – full overdefined matrix", but with noticeable lower-quality results

The "Subframe disconnected – square matrix" produced nearly identical results to the "Subframe disconnected – full overdefined matrix" condition. Typically over-defining the matrix provides better results. In this case, the model is essentially simple, with most of the noise traveling through the Z direction of the top shock mount, and with the appropriate matrix conditioning applied, the results were very close

The time-domain analysis added the ability to listen to the results of the SPC analysis. The results were the same as that of the frequency-domain analysis.

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