A comparison of characterization methods for automotive steering pump vehicle airborne noise paths

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ABSTRACT

This paper discusses and compares four different methods for calculating airborne transfer path functions for noise radiated from an automotive hydraulic steering pump in a vehicle. The four methods included here were all based on measurements of steering pump sound power, or volume velocity derived from sound power, and were considered as part of a larger study to identify automotive hydraulic steering system noise transmission paths. The theory behind each of the four approachs is developed and experimental results demonstrating the relative efficacy of each method are shown. Lastly, the merits and limitations of these experimental methods are discussed.

1. INTRODUCTION

In recent decades, automotive transfer path analysis has evolved into a critical tool for quantifying not only the contributions of individual vehicle components to noise and vibration perceived by vehicle occupants, but also the sensitivity of the vehicle to the NVH characteristics of these components. For automotive hydraulic steering systems three noise paths exist: airborne, structure borne and fluid borne. Earlier work by Fernholz and Nessler[1] discussed a method for comprehensively measuring all three of these paths. The objectives of the present study were not only to refine the airborne noise path characterization portion of this earlier work, but to also select a test method for doing so which was practical and expedient.

Four methods for measuring automotive hydraulic steering system airborne noise paths were considered. The four methods differed in the manner in which the airborne noise transfer function of the vehicle was measured, and in the type operating data which was combined with this transfer function to predict vehicle interior sound pressure level.

2. THEORY

Each of noise path methods considered in the present work quantified vehicle sensitivity to airborne noise from the steering pump. To compute an interior noise contribution, these path sensitivities were in turn combined with either test bench sound power operating data from the steering pump or steering pump volume velocity computed from sound power. This section describes the mathematical approach behind each of the noise path test methods.

A. Steering Pump Sound Power and Volume Velocity

Sound power for the hydraulic steering pump was measured using SAE standard procedure J2747[2, 3]. Using this procedure, sound pressure levels were measured in the free field of the pump with a hemispherical array of nineteen microphones. Sound power was then computed from

$$L_w = \overline{L}_p + 20\log(r) + 8 \tag{1}$$

where L_w was sound power level, $\overline{L}_p$ was the average sound pressure level for the microphones in the array and r the radius of the array in meters.

One of the four noise path measurements, the "room constant method" (see below), used steering pump sound power to compute interior noise contribution. The remaining three methods all used steering pump acoustic volume velocity rather than sound power. The volume velocity for the pump, Q_p, was calculated from the sound power data, with the simplifying assumption that the steering pump could be reasonably represented by a pulsating sphere of radius a. For such a source, volume velocity was computed from sound power as

$$Q_p = \frac{2}{k}\sqrt{\frac{\sqrt{2}\pi}{\rho c}\Pi\left(1 + (ka)^2\right)} \tag{2}$$

where ρ was the density of air, c was the wave speed in air, k the wave number and Π the sound power[4].

B. Room Constant Method

For the room constant transfer path calculation method, the vehicle airborne path sensitivity was assumed to be a function steering pump sound pressure incident on the front-of-dash (FOD) panel, P_{FOD}, and of the apparent noise reduction (ANR) properties of the FOD panel. This incident sound pressure was in turn assumed to be a function of the reverberation properties of the vehicle engine compartment.

Steering pump sound pressure level at the FOD panel was computed from

$$_{FOD}L_p = L_w + 10\log\left(\frac{Q_\theta}{4\pi s^2} + \frac{4}{R}\right) \tag{3}$$

where Q_θ was the source directivity (assumed to be 1 for this work), s was the distance from the source to the measurement location, and R was the room constant in metric sabins[5]. As described in the references[1], R was calculated from T_{60} reverberation decay measurements of the engine compartment as

$$R = \frac{0.161VS}{T_{60}S - 0.161V} \tag{4}$$

where S was the surface area of the engine compartment volume in m^2, V was the volume of the engine compartment in m^3 and T_{60} was the measured reverberation decay time in seconds. FOD panel ANR was quantified from sound pressure level differences measured between vehicle interior microphones and surface microphones mounted directly to the engine-side surface of the panel. Interior noise levels were thus predicted from

$$P_{pred} = P_{FOD}ANR \tag{5}$$

where P_{FOD} was the sound pressure calculated from Equation (3).

C. Reciprocal Method

With the reciprocal method approach, a volume velocity noise source (VVS) was placed in the vehicle interior at the driver's left (outboard) ear location. The response at the steering pump on the vehicle engine was measured using four surface-mount microphones. A P/Q transfer function for the vehicle was then computed. Interior steering system noise levels were predicted from

$$P_{pred} = \left[\frac{P}{Q}\right] Q_p \tag{6}$$

One advantage of this method was that it directly measured the transfer path from the pump to the vehicle interior. Measurements of intermediate transfer functions (e.g. FOD panel ANR) were not required.
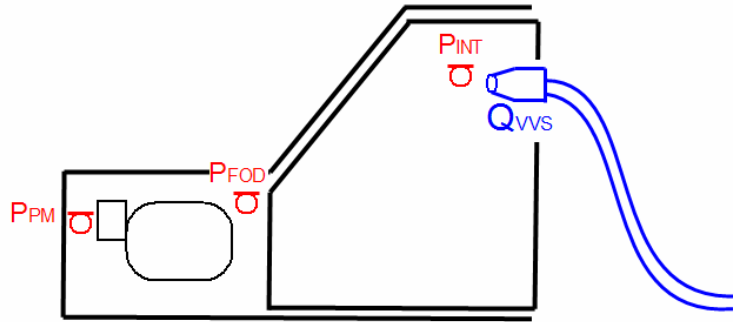

Figure 1: Reciprocal method.

D. Boundary Condition Transfer Function Method

Of the airborne noise measurement methods considered here, the boundary condition transfer function method was perhaps the most complex. For this method, steering pump sound pressure incident on the FOD panel was estimated from the free-field test bench measurements of steering pump sound power combined with experimental measurements of the engine compartment airborne noise transfer function from the pump to the FOD panel.

The engine compartment boundary condition transfer function was measured by removing the steering pump from the vehicle and positioning a noise source in its place. Sound pressure at the FOD panel, $P_{FOD\ eng\ comp}$, was then measured and compared with the VVS sound pressure that would have been measured in a free field condition, $P_{FOD\ FF}$. The boundary condition transfer function was computed from these measurements as

$$BC_{eng\ comp} = \left[\frac{P_{FOD\ eng\ comp}}{P_{FOD\ FF}}\right] \tag{7}$$

In other words, $BC_{engcomp}$ represented the airborne transfer function of the engine compartment from the steering pump location to the FOD panel.

The predicted sound pressure level at the FOD panel, $P_{FOD\ pred}$, was computed by multiplying the steering pump free field sound pressure level with the transfer function shown in Eq. (7). The steering pump free field sound pressure, P_{FODLw}, was computed from the steering pump test bench sound power data using Eq. (1). Combining these computational steps, vehicle interior steering noise for the boundary condition transfer function method was calculated as

$$P_{pred} = P_{FOD\ pred} ANR \tag{8}$$

where

$$P_{FOD\ pred} = P_{FOD\ L_w} BC_{eng\ comp} \tag{9}$$

E. Volume Velocity TF Method

For the fourth method considered in this study, the volume velocity TF method, an airborne noise transfer function from the steering pump engine location to the vehicle FOD panel was calculated using a reciprocal measurement method. A VVS was placed at the FOD panel and the sound pressure at the steering pump location was measured, resulting in a P/Q transfer function for this path. Steering pump volume velocity was computed using Eq. (2), and applied to the P/Q transfer function to estimate steering pump sound pressure at the FOD panel. Lastly, vehicle interior steering sound pressure was predicted by multiplying the predicted FOD sound pressure with the ANR function for the FOD panel.
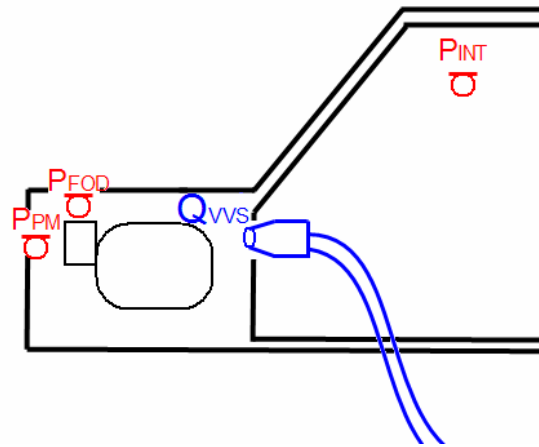

**Figure 2: Volume velocity TF method.**

3. RESULTS AND DISCUSSION

Sound power levels for the orders of the steering pump used in this study were computed using Eq. (1). The sound pressures used for this computation are shown in Figure 3. Volume velocity for the pump was in turn calculated from sound power using Eq. (2). Volume velocity is in Figure 4. Note that for purposes of providing a compact summary of the data, the envelope of maximum order levels is shown in this plot, rather than the individual steering pump orders.

The relative advantages and disadvantages of the various methods were evaluated by comparing experimental time requirements, necessary assumptions, and the quality of results with respect to measured interior sound. All methods evaluated required the operating noise of the pump to be measured on a test stand in a certified chamber. All methods also used a point source and various microphones in different capacities, so there was little difference in hardware cost between the four methods.
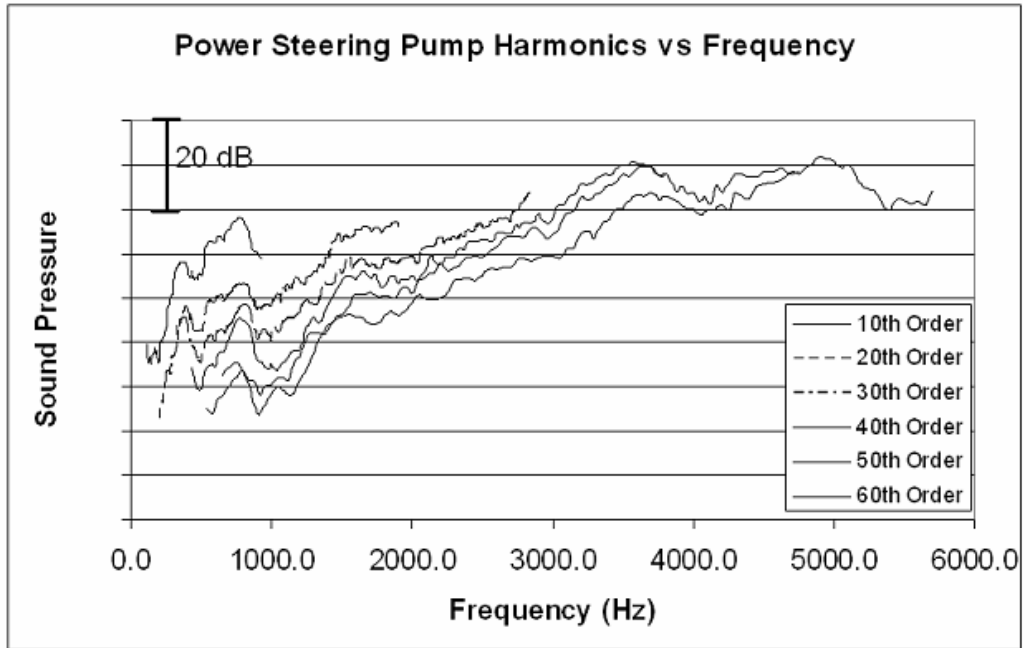
Figure 3: Steering pump sound pressure levels measured on a test bench uinsg SAE J2747. Levels for the first six pump orders are shown.
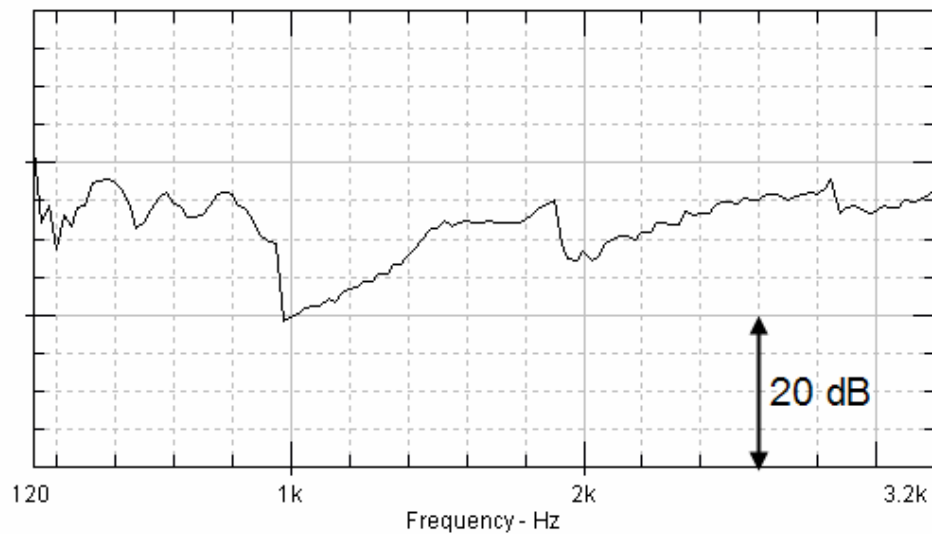
Figure 4: Volume velocity versus frequency for the steering pump, maximum envelope of pump harmonics.

To aid in the comparison of these results, the predicted levels were "normalized" by computing an equivalent P/Q transfer function for each case from the predicted interior sound pressure level and the steering pump volume velocity function shown in Figure 4. This comparison is shown in Figure 5. Again, as was the case for volume velocity, the maximum envelope of the steering pump orders is used to provide a compact summary of the P/Q transfer functions.
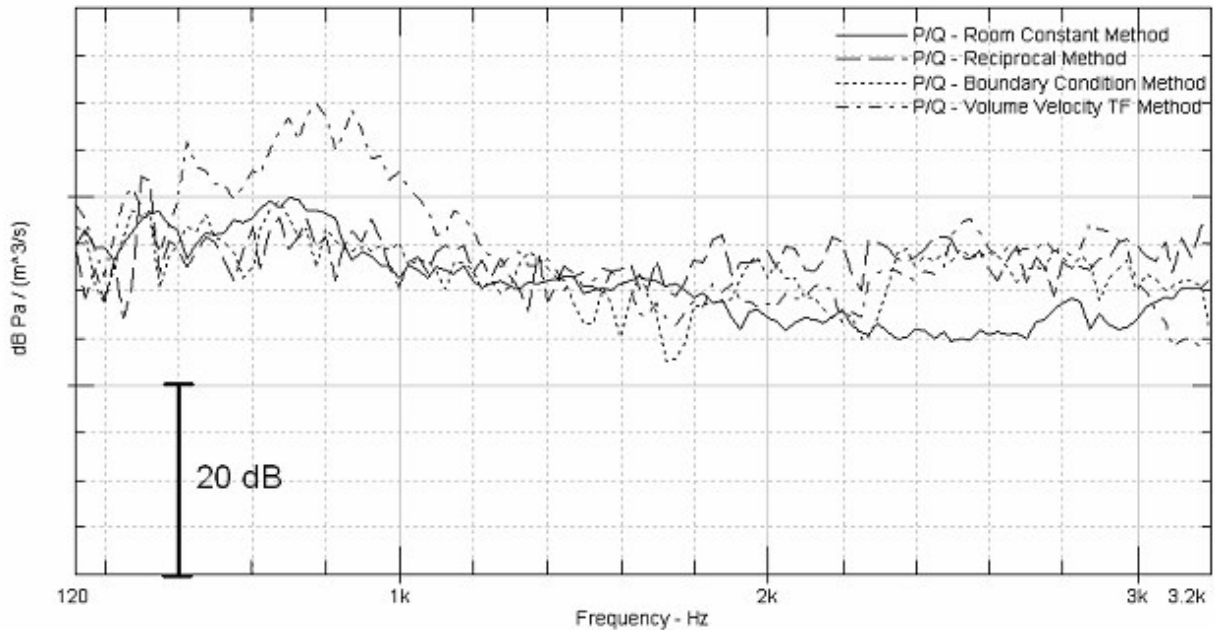
Figure 5: Comparison of P/Q transfer functions for all four methods.

The first method, the room constant method, under predicted the airborne contribution for the first two steering pump harmonics. This method also required several assumptions to be made regarding source directivity, engine compartment surface area and volume, all of which could contribute to error. This method required little measurement time, but significant processing time.

The fourth method considered, the volume velocity TF method, over predicted the airborne contribution between 600 – 1000Hz. This method assumed reciprocity of the transfer function between the source and boundary locations (i.e. from the steering pump location on the engine to the FOD panel). This assumption may have been overly simplistic, considering the diffuse nature of the engine compartment. This method was also complicated by the measurement time required to effectively place the point source at various locations about the front of dash.

The reciprocal and boundary condition methods yielded virtually identical results. Considering the time needed to measure the transfer functions and calculate the attenuated noise in free field for the boundary condition method, it is recommended that the reciprocal method be used for such testing. This would also exclude any potential error in using the vehicle's ANR curve that may affect contribution results.

As a final evaluation of the reciprocal transfer path method, a comparison of the airborne contribution to interior sound pressure level computed using this method was made to the actual sound pressure levels measured in the vehicle. Figure 6 shows the results of this comparison for the steering pump 20th through 50th orders. The levels predicted using the reciprocal method generally followed the actual levels measured in the vehicle, with the exception of frequencies near 1 kHz. Additionally, for frequencies between approximately 1.4 kHz and 1.8 kHz, the 50th pump order contribution levels predicted using the reciprocal method were generally higher than the levels measured in the vehicle. It is possible that airborne noise levels measured at these frequencies were attributable to another path in the vehicle (e.g. structure borne). It is also possible that due to mounting differences, the actual radiated noise measured from the steering pump on the test bench was different from the noise levels measured in the vehicle.
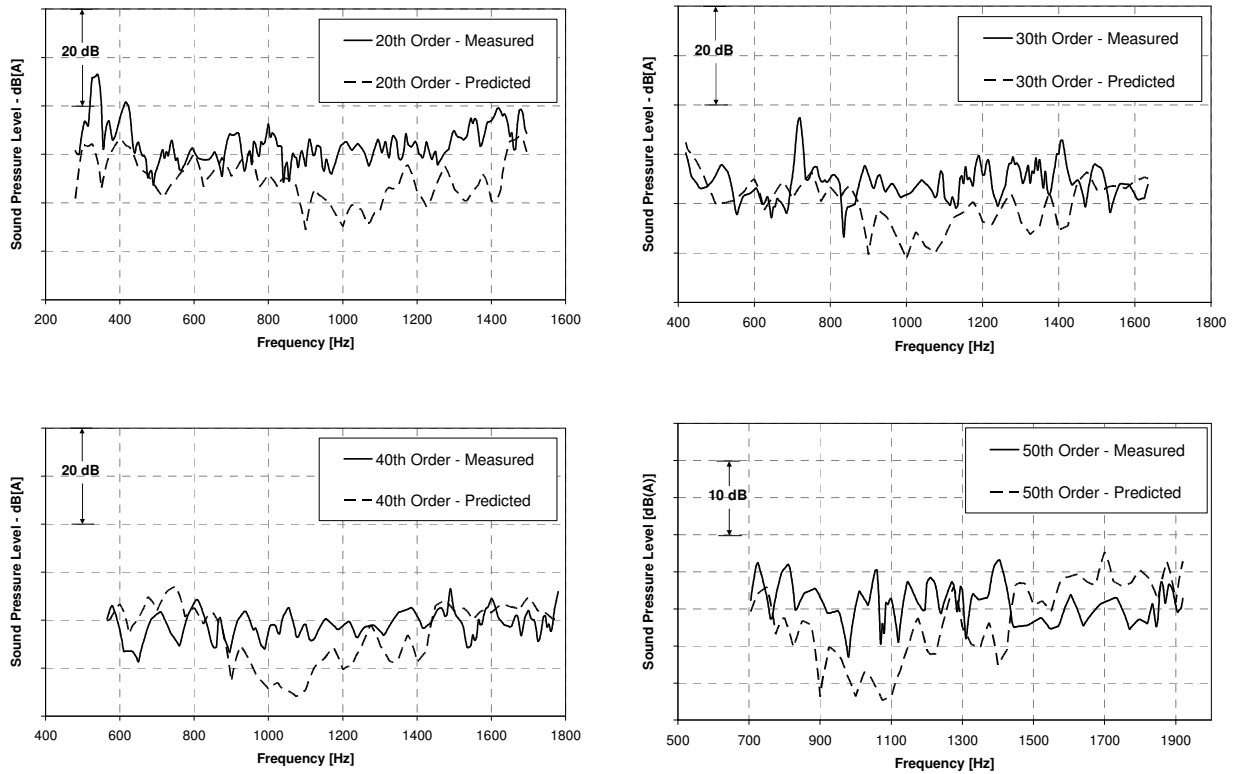
Figure 6: Comparison of interior noise levels predicted using the reciprocal method and actual measured interior sound pressure levels for the 20th through 50th pump orders.

4. CONCLUSIONS

This work has explored four different methods for computing automotive steering system vehicle interior airborne noise contribution levels. Each of these four methods used steering pump component test bench sound power measurements as the operating data source for the contribution analysis. At the vehicle level, only one method, the reciprocal method, used a "global" vehicle transfer function from the pump to the interior microphone locations. The remaining three methods all predicted steering pump sound pressure at the FOD panel (P_{FOD}), then multiplied this level with the FOD panel ANR function to compute interior sound pressure.

Of the four methods considered, the reciprocal method yielded reasonable results with a minimal expenditure of effort. In addition to the benefit of a relatively simple experimental setup, the actual measurement time and equipment requirements for this method were lower than the requirements for the other three measurements.

5. ACKNOWLEDGEMENTS

[1] Fernholz, C., Nessler, G., "Prediction of Vehicle Steering System NVH from Component-Level Test Data", SAE 2006-01-0483.

[2] "Hydraulic Pump Airborne Noise Bench Test", SAE standard procedure J2747.

[3] Fernholz, C., Offerle, T., Beyerlein, R., Stevenson, W., Wood, M., "SAE Standard Procedure J2747 for Measuring Hydraulic Pump Airborne Noise", SAE 2007-01-2408.
[4] Temkin, S., "Elements of Acoustics", Acoustical Society of America, 2001.
[5] Lord, H., Gatley, W., Evensen, H., "Noise Control for Engineers", Krieger Publishing, 1980.