Approximating Engine Tailpipe Orifice Noise Sound Quality using a Surge Tank and In-Duct Measurements

Paul M. Radavich
Ford Motor Company

Ahmet Selamet
The Ohio State University

ABSTRACT

Because of the need to safely vent exhaust gases, most engine dynamometer facilities are not well suited to measuring engine exhaust orifice noise. Depending on the location of the dyno facility within the building, the exhaust system may need to be extended in order to properly vent the exhaust fumes. This additional ducting changes the acoustic modes of the exhaust system which will change the measured orifice noise. Duct additions downstream of the original orifice location also alter the termination impedance such that in-duct pressure measurements with and without the extended exhaust system can vary significantly. In order to minimize the effect of the building’s exhaust system on the desired engine exhaust system measurements, the present approach terminates the engine exhaust into a large enclosed volume or surge tank before venting the gases into the building’s ventilation system. The large volume of the surge tank produces acoustic reflections similar to those of an orifice open to the atmosphere. Two pressure transducers upstream of the surge tank are used to separate out the forward and backward traveling acoustic waves in the duct and approximate the particle acceleration at the exhaust orifice location using linear acoustic assumptions. The radiated orifice noise is then estimated from the particle acceleration using a simple source model. Comparisons of this approximated orifice noise with the actual external measurements reveal that this method correctly captures trends in the dominant engine orders and predicts the amplitudes of these orders within about 5 dB.

INTRODUCTION

Measuring engine exhaust orifice noise on a dynamometer typically requires a facility built specifically with exhaust noise measurements in mind. For indoor facilities, the tailpipe is usually routed to an isolated anechoic chamber which allows the engine radiated noise to be separated from the tailpipe orifice noise. This requires a dedicated room for measurement, however, along with a separate ventilation system to remove the exhaust gases from this room. Alternately, if the dyno room is constructed adjacent to the exterior wall of the building, the tailpipe can be routed through the wall and the noise measurements taken outside the building. This type of arrangement is not possible in many buildings though. The present work investigates a technique for measuring the exhaust orifice noise when a dedicated facility similar to those described above is not available and the engine exhaust must be connected to a ventilation system within the building.

In the present approach, the tailpipe is routed into a large chamber or surge tank before entering the building ventilation system. If the surge tank is properly designed, the reflections from the tailpipe at the surge tank will be similar to the reflections from an open ambient. As long as the original tailpipe length is maintained when the surge tank is added to the system, the acoustic properties of the original system are retained.

Following this introduction, the methodology section describes how two pressure transducers placed in the tailpipe can be used to separate out the forward and backward travelling waves in the
tailpipe using the two-microphone technique (ASTM, 1990; Chung and Blaser, 1980). This is then used to approximate the particle acceleration at the tailpipe opening and estimate the radiated noise at a distance from the tailpipe. Next, the experimental setup used to validate this approach is discussed. Experiments were performed both with and without the surge tank in order to separate out deviations caused by the 2-microphone methodology from those introduced through the addition of the surge tank. Results for these two configurations are then presented and compared to the actual externally measured orifice noise.

METHODOLOGY

Using a variation of Landau and Lifshitz (1959), the radiated pressure at a distance $R$ from the open end of an un baffled pipe can be written as

$$p(R) = \left(\frac{\rho_a r^2}{4R}\right)\frac{\partial u}{\partial t}$$

(Jones and Brown, 1982). In Eq. (1), $r$ is the tailpipe radius, $\rho_a$ is the density of the ambient air, and $\partial u/\partial t$ is the particle acceleration at the open end of the tailpipe as shown in Figure 1. Thus, if the particle acceleration at the tailpipe can be estimated using in-duct measurements, the radiated noise can be calculated using Eq. (1).

For four-stroke engine pulsation noise, the frequency of the noise is linked to the engine order and engine rpm through the relationship

$$f(\text{Hz}) = \frac{\text{Order} \cdot \text{RPM}}{60}.$$  (2)

For engine exhaust noise, a majority of the energy is typically contained below 10th order. Assuming a maximum engine speed of 6000 rpm, this places the maximum frequency of interest in the 1000 Hz range. For propagation in a circular duct (which is typical for engine exhaust systems) the wave will remain planar for frequencies well below the cutoff frequency for higher order mode propagation. Assuming the non-symmetric mode is the first to propagate, this limit is given by

$$f < \frac{c}{2\pi} \left(\frac{1.841}{r}\right).$$  (3)

where $c$ is the speed of sound and $r$ is the radius of the duct (Selamet and Radavich, 1997). For the experiments in this study, the exhaust gas temperature remained above 700 K which places the minimum speed of sound above 515 m/s ($c = \sqrt{\gamma RT}$ assuming $\gamma = 1.32$ and $R = 287$ J/kg K for the exhaust gases). For an internal pipe diameter of 7.24 cm this places the cutoff frequency at 2084 Hz which is well above the 1000 Hz frequency of interest. Thus, for the present experiments, the wave propagation in the tailpipe can be considered one-dimensional.
Although pressure amplitudes in the exhaust system can be highly non-linear, the in-duct measurements for this investigation were taken downstream of a catalytic converter and muffler, thus reducing the amplitudes substantially. In-duct sound pressure levels for the present measurements were typically in the 120-140 dB range with only a few data points exceeding these levels. Although these levels are at the upper limits of linear acoustic theory, the low frequencies and relatively short propagation distances are expected to minimize the non-linear effects.

Under the one-dimensional and linear conditions outlined above, the propagation of acoustic pressure waves in the tailpipe are governed by the wave equation

\[
\frac{\partial^2 p}{\partial t^2} + 2U \frac{\partial^2 p}{\partial x \partial t} + (U^2 - c^2) \frac{\partial^2 p}{\partial x^2} = 0 ,
\]

where \( U \) is the mean flow velocity in the tailpipe (Munjal, 1987). The solution to Eq. (4) is a pressure wave of the form

\[
p(x, t) = (Ae^{-ik^+x} + Be^{ik^-x}) e^{i\omega t} ,
\]

where \( A \) and \( B \) represent forward and backward traveling waves,

\[
k^+ = \frac{\omega}{c+U} ,
\]

\[
k^- = \frac{\omega}{c-U} .
\]

\( \omega = 2\pi f \) is the angular frequency, and \( i = \sqrt{-1} \).

Using the upstream pressure transducer as a reference for distance along the pipe \( (x = 0) \) as shown in Figure 1 and removing the cyclic dependence \( e^{i\omega t} \), the pressure at this upstream transducer can be written from Eq. (5) as

\[
p_1 = A + B .
\]

At a distance \( s \) downstream \( (s \) is the microphone spacing distance in Figure 1) the propagation of these waves causes a change in the phase

\[
p_2 = Ae^{-ik^+s} + Be^{ik^-s} .
\]

All of the pressures in Eqs. (8) and (9), \( p_1, p_2, A, \) and \( B \) are complex quantities. Therefore, Eqs. (8) and (9) each represents two equations; one for the real component and one for the imaginary component. Since \( p_1 \) and \( p_2 \) are both known from measurements (both real and imaginary components), Eqs. (8) and (9) represent four equations to solve for the four unknowns \( A_{real}, A_{imag}, B_{real}, \) and \( B_{imag} \).

Using the linearized momentum equation

\[
\frac{\partial u}{\partial t} + U \frac{\partial u}{\partial x} + \frac{1}{\rho} \frac{\partial p}{\partial x} = 0 ,
\]

\( \rho \) is the in-duct density) the particle velocity at the open tailpipe end \( (x = L) \) can be solved as

\[
u = \frac{1}{\rho c} \left( Ae^{-ik^+L} - Be^{ik^-L} \right) e^{i\omega t} .
\]

This velocity is then differentiated with respect to time which yields the particle acceleration at the open tailpipe end

\[
\frac{\partial u}{\partial t} = \frac{i\omega}{\rho c} \left( Ae^{-ik^+L} - Be^{ik^-L} \right) e^{i\omega t} .
\]

Thus, from the two pressure transducer measurements \( p_1 \) and \( p_2 \), Eqs. (8) and (9) can be used to solve for the complex wave amplitudes \( A \) and \( B \). Substituting these into Eq. (12) provides the particle acceleration which, when combined with Eq. (1), estimates the noise radiated from the tailpipe at a distance \( R \).

EXPERIMENTS

In order to evaluate the accuracy of this method, two sets of experiments were performed at the Center for Automotive Research of The Ohio State University as illustrated in Figure 2. This figure shows that a partition is available in the dyno facility which allows the exhaust to be directed outside of the building. In the first set of experiments illustrated in Figure 2a, the tailpipe is open to ambient and a microphone placed 0.5m from the tailpipe at 45 degrees is used to directly measure the radiated noise. Two *Kistler® 4045A2 water cooled pressure transducers were also placed in the tailpipe separated by a distance \( s = 25.4 \text{ cm} \). In this

* Kistler® is a registered trademark of Kistler Instrument Corporation of Clarence, N.Y.
experiment, the radiated noise obtained using Eqs. (1) and (12) can be compared directly with the external microphone measurement. In the second set of experiments shown in Figure 2b, a surge tank is added to the system. By testing the surge tank separately, the two-pressure transducer results from the configurations in Figures 2a and 2b can be compared to determine the effect of adding the surge tank on the tailpipe reflections. Note that an equivalent tailpipe length was maintained both with and without the surge tank.

Both sets of experiments were conducted using a V8 engine with a fairly equal length Y-pipe, a catalytic converter, and a muffler. In addition to the in-duct pressure measurements, the temperature at the pressure transducer #1 location was also recorded as well as the mass flow rate in the system. In view of the ideal gas law, the temperature and pressure measurements yield the density at the transducers for use in Eq. (12). This equation also requires the mean flow velocity $U$, which was calculated from the density, mass flow rate, and cross-sectional area of the tailpipe.

It is noted here that the Kistler® pressure transducers were used without any sort of phase calibration. The two-microphone technique described in the Methodology section is based on measuring small phase differences in the waves as they pass the microphones. At low frequencies in particular, where the wavelengths are large, the phase difference in the waves between the two microphones becomes small and any sort of phase error between the two transducers can contaminate the results. Although the results presented in the following section are favorable, additional refinement may be achieved through more elaborate phase calibration of the two pressure transducers.

RESULTS

The external microphone measurements of Figure 2a as well as the two-pressure transducer inferred results with and without the surge tank from Figures 2a and 2b are compared in Figures 3 through 10. These plots display engine orders 1 through 4 and 8 which is where a majority of the acoustic energy was located. The external microphone was also used to provide a measure of the overall sound pressure

Figure 2: Experimental test setup: (a) without surge tank; (b) with surge tank.
Figure 3: Comparison of measured 1.0 engine order exhaust radiated orifice noise with the orifice noise inferred using the two-microphone technique (both with and without a surge tank).

Figure 4: Comparison of measured 1.5 engine order exhaust radiated orifice noise with the orifice noise inferred using the two-microphone technique (both with and without a surge tank).
Figure 5: Comparison of measured 2.0 engine order exhaust radiated orifice noise with the orifice noise inferred using the two-microphone technique (both with and without a surge tank).

Figure 6: Comparison of measured 2.5 engine order exhaust radiated orifice noise with the orifice noise inferred using the two-microphone technique (both with and without a surge tank).
Figure 7: Comparison of measured 3.0 engine order exhaust radiated orifice noise with the orifice noise inferred using the two-microphone technique (both with and without a surge tank).

Figure 8: Comparison of measured 3.5 engine order exhaust radiated orifice noise with the orifice noise inferred using the two-microphone technique (both with and without a surge tank).
Figure 9: Comparison of measured 4.0 engine order exhaust radiated orifice noise with the orifice noise inferred using the two-microphone technique (both with and without a surge tank).

Figure 10: Comparison of measured 8.0 engine order exhaust radiated orifice noise with the orifice noise inferred using the two-microphone technique (both with and without a surge tank).
The flow noise levels were chosen as an upper bound on the noise excluding the engine half orders in the 1 to 4 engine order range. As an example of this, Figure 11 shows the external microphone data at 3500 rpm along with the chosen flow noise level. Excluding the engine related noise at 1.0, 1.5, 2.0, and 4.0 order the rest of the background noise is approximately 75 dB or less. Note that because of the background noise in Figure 11, it is difficult to distinguish some of the engine orders, such as 2.5, 3, and 3.5, from the background noise. Because it is unknown whether the engine order content or the flow noise is being measured at these orders, the data at points near and below the flow noise level are deemed unreliable. As shown in Figures 3 through 10, the flow noise increases and becomes more significant at higher rpm. In Figures 5 through 10, data points for which the in-duct sound pressure levels were low are also labeled. The Kistler® 4045A2 pressure transducers have a rated threshold of < 134 dB. Examining the data reveals that many of the data points are below this level while still producing acceptable results. The data points 10 dB or more below this threshold have been labeled and may be questionable in their accuracy.

The results in Figures 3 through 10 show that the two-pressure transducer method generally reproduces the relative trends and amplitudes of the various engine orders. The dominant 2.5, 3, and 4th orders show very good correlation over most of the rpm range. The low frequency 1.0 and 1.5 order results in Figures 3 and 4 are under-predicted across the rpm range which may be partially due to the unbaffled source assumption made in Eq. (1). Although the tailpipe is extended away from the building in the experiments, at extremely low frequencies the baffling from the building and the ground may tend to increase the externally measured sound pressure levels. For data points with good signal to noise ratios, the two-transducer method is typically accurate within about 5 dB with a few points deviating by as much as 10 dB. Comparison of the two-microphone results with and without the surge tank show that the effect of adding the surge tank as a replacement for the ambient are typically small. There are only a few points with a strong signal where the surge tank changes the results by more than about 2 dB.
CONCLUSIONS

This work presents a technique for inferring exhaust tailpipe radiated noise when it cannot be measured directly by using two in-duct pressure transducers and a surge tank placed at the tailpipe opening. Results comparing this technique with actual external radiated noise measurements for a firing V8 engine reveal that the technique is appropriate for measuring the relative order content of the exhaust noise. The dominant engine orders were reproduced within 5 dB with all results within 10 dB of the measured external noise.

Future work to refine this method will investigate improving the two-microphone technique by phase calibrating the pressure transducers. Improvements can also be made in the radiation model of Eq. (1) for experiments where an anechoic chamber is not available for the external noise measurements and some baffling from the surrounding environment may occur. An additional analytical work is also being performed on optimizing the shape and dimensions of the surge tank to minimize the effect of replacing the open ambient with the surge tank.

REFERENCES


