1999-01-1652

Simulating Odd Fire V-10 Exhaust Noise for Sound Quality Evaluation

P. Hetherington, W. Hill, F. Pan, B. Snider
Tenneco Automotive, Grass Lake, MI, USA

E. Bradamante
Ricardo Inc., Burr Ridge, IL, USA

G. Cerrato-Jay
MTS Systems, Noise and Vibration Division, Madison Heights, MI, USA

ABSTRACT

This paper presents an integrated design/simulation/test approach for evaluating the sound quality of exhaust noise as early as possible in the exhaust system design and development process. A time domain engine/exhaust simulation program is used to calculate the engine order content of the tailpipe radiated noise from an odd fire V-10 exhaust system. Both steady state and transient conditions are simulated and sound files generated for exhaust sound quality evaluation. To increase the realism of played back sounds, the predicted engine orders are mixed with synthesized or recorded background noise for both steady state and transient conditions. These alternative approaches will be described and evaluated for technical feasibility and sound quality.

INTRODUCTION

During an investigation into an interior boom problem on a 1998 Dodge Viper it was discovered that one source of the problem was a high level of 2.5 order exhaust noise. This seemed unusual because a very symmetric exhaust system like the Viper's normally has predominately integer orders (5.0, 10.0, 15.0 etc. orders for a V-10). Typically exhaust noise half orders occur when the exhaust system is asymmetric, for instance when the legs of the Y-pipe are of unequal length on a V engine. In the case of the Viper, it is the engine cylinder firing that is asymmetric because it is an odd-firing V-10.

To reduce the level of the 2.5 order in the RPM range of interest, a new asymmetric exhaust system was designed. The effect of the new exhaust system was predicted by using a time-domain simulation program. The predicted output of this program can be "auditioned" but sometimes lacks a realistic sound quality. In order to improve the realistic quality of the reproduced sounds, digital filtering techniques were applied to create a "virtual" tailpipe noise. In order to do this, binaural noise recordings at the tailpipe of the vehicle with the baseline exhaust system were measured under various operating conditions. Then the measured baseline background noise and predicted order noise were combined to create the "virtual" tailpipe noise. If the prediction is accurate, the effect on the sound quality of the new muffler can be evaluated early during the design phase, with no need for actually building and testing multiple prototypes.

In a previous paper [1], a method was developed to evaluate exhaust sound quality by filtering baseline recorded noise with insertion loss predicted by a frequency domain program called LAMPS [2]. That technique however would not work for this application because the proposed exhaust system modifications would affect the modeled source. On the other hand, the frequency domain program assumes the noise source characteristics (source strength, impedance and frequency content) are the same for all modeled systems.

This paper describes an alternative method which has been utilized to produce realistic sounds from simulated exhaust design changes by applying digital filtering techniques to individual engine orders [3].

DESIGN OF THE EXHAUST SYSTEM

The Viper engine is a 90 degree V-10 with a single pin crankshaft. The result is that the cylinder firing sequence has uneven intervals (90-54-90-54-90-….degrees) which is called “odd-firing”.

An even firing V-10 would have equal intervals between cylinder firings (72-72-72-72-…degrees) but would require a split pin crankshaft or a 72 degree V block angle. When the noise pulses from the two five cylinder banks add together in the rear muffler (Figure 1), the result is not a smooth 5.0 order dominated sound. Instead the noise from the tailpipes is closer to a rough 5 cylinder quality with a high level of 2.5 order noise.

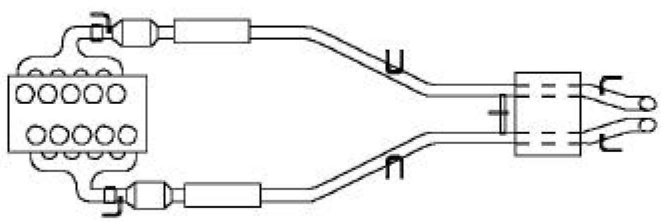

Figure 1. Baseline exhaust system

To reduce the level of the 2.5 order noise an asymmetric exhaust system was proposed. The basic idea was to delay one bank of exhaust pulses by adding length to one side of the exhaust system (Figure 2).

The effect of the proposed exhaust system on tailpipe noise was predicted by simulation with a time domain engine modeling program called WAVE.

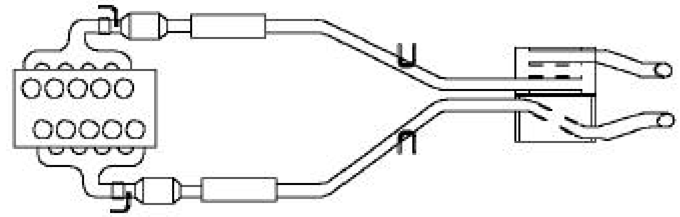

Figure 2. Proposed exhaust system

EXHAUST NOISE PREDICTION

WAVE is an engine performance and gas dynamic simulation software developed by Ricardo [(4)]. The program is based on 1-dimensional flow in ducts and on quasi-3-dimensional representation of volumes. WAVE provides a sufficiently accurate simulation of the gas flows throughout the entire engine system by solving 1-dimensional Navier-Stokes equation with control volume techniques.

WAVE was first applied to model the baseline production exhaust system of the Viper. The WAVE model was built using KADOS, a pre-processor to WAVE which can automatically mesh for complex geometry systems such as mufflers interiors. The intake and exhaust parts of the model were constructed using detailed technical drawings and the actual hardware measurements. Engine data such as valve lift profiles, port flow coefficients, and information on in-cylinder heat transfer and combustion were based on provided information and proper engineer assumptions.

The model of the baseline system was then calibrated in terms of engine performance as well as radiated noise. For the measured engine performance, full load dynamometer data were provided by DaimlerChrysler. The calibration involved mainly adjustments of flow losses in the intake and exhaust system, of the heat release curve and of the coefficients in the mechanical friction model. Figure 3 below shows the comparison of measured and predicted engine power under motoring conditions, while Figure 4 shows the same comparison under full load conditions..

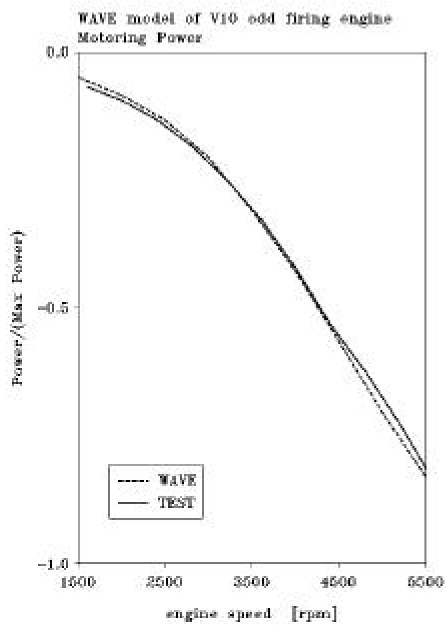

Figure 3. Measured and predicted absorbed engine power under motoring conditions

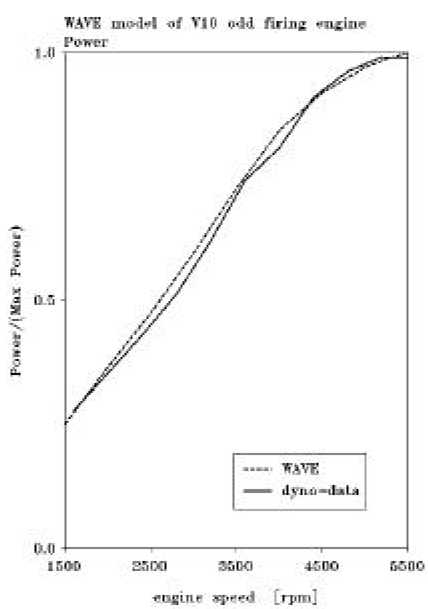

Figure 4. Measured and predicted engine power under full load conditions

Figure 5 shows the comparison between measured and predicted specific fuel consumption, while Figure 6 shows the comparison of maximum cylinder pressure.

For the acoustical calibration, tailpipe noise was recorded by Tenneco Automotive on the chassis dynamometer during slow, part throttle acceleration.

Tailpipe noise was recorded, with a single microphone, 0.63m out, 0.15m up from the central axis of the dual tailpipes. The radiated noise was then predicted at the microphone location. The calibration of tailpipe noise was achieved by adjusting the throttle openings throughout the transient runup simulation. Measured and predicted engine orders are compared in Figure 7.

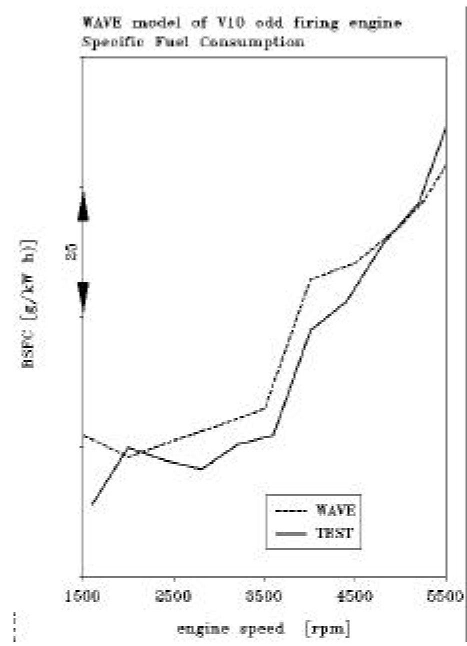

Figure 5. Measured and predicted specific fuel consumption

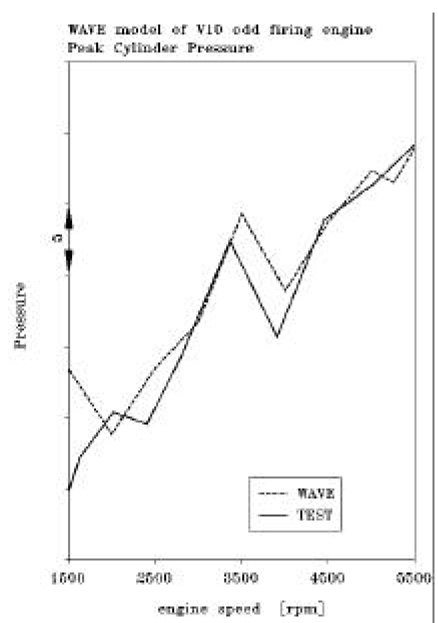

Figure 6. Measured and predicted maximum cylinder pressure

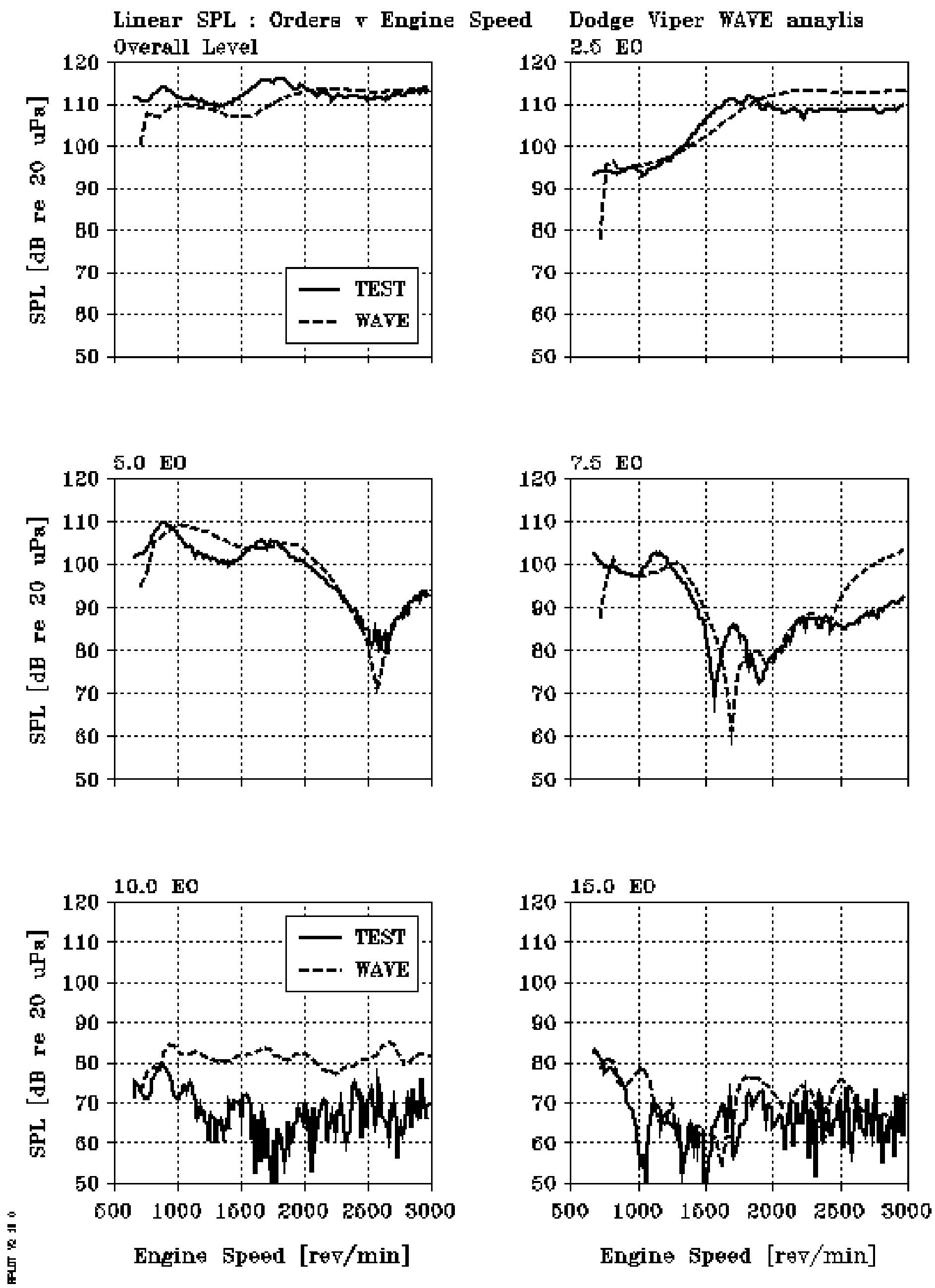

Figure 7. Measured and predicted tailpipe noise: overall and orders 2.5, 5, 7.5, 10 and 15

The data shown above demonstrate a good correlation between experimental and analytical data, therefore it is proper to simulate the proposed change to the baseline exhaust system with this WAVE model.

The noise file predicted by WAVE is a single channel time history in AIFF format, with the tachometer pulse embedded in the 16th bit. The predicted sound files were then post-processed with the MTS Sound Quality Engineering system.

SOUND QUALITY ASSESSMENT OF BASELINE SYSTEM

In addition to the single microphone recordings carried out on the chassis dyno to calibrate the WAVE model (discussed in the previous section), binaural recordings were also performed in the same conditions in which product design and development engineers use to evaluate the exterior sound quality of the exhaust noise.

A binaural head was positioned 1m out and 1.6m up from the tailpipes on the test track at the Tenneco

Automotive R&D Center in Grass Lake, MI (Figure 8). Several conditions were recorded: idle, various fixed engine speeds, slow runup in neutral, free kicks (quick engine acceleration in neutral), and slow, medium and WOT drive-aways. All binaural data were recorded simultaneously with a wireless optical tachometer. The optical tach was required because of the odd-fire ignition signal and the wireless broadcasted tach signal allowed recording during drive-aways.

Figure 8. Test setup and vehicle at the test track

The analysis of the binaural recordings and the digital filtering of all sound files were performed using the MTS Sound Quality Engineering system [5].

The 2.5 order is, under most conditions, the dominant order in the exhaust noise signature of the Viper. In general, orders 2.5 through 15, step 2.5, exhibit the higher levels. This is particularly evident at idle, as shown by the plots in Figure 9. The data shown are the results of a time averaging process of the binaural data performed synchronously to the engine tachometer. The temporal average, phase-referenced to the engine, allows the enhancement of the periodic components with the same period as the engine rotational speed while at the same time decreasing the level of the non-periodic components. The upper plot in Figure 9 displays the average time history which corresponds to 2 rotations of the engine (the main sine component is repeated 5 times, which corresponds to the 5^{th} order). The lower plot displays the corresponding order spectrum with the 2.5, 5, 7.5, 10, 12.5 and 15 orders above all others.

The order spectra at idle is characterized by a typical “rumble” characteristic, which is explained by the interaction of the three main tones (2.5, 5, and 7.5 order) which are spaced 28 Hz apart. A different perception is induced by the runup in neutral, where basically the only order present is the 2.5 and the signature sounds much more “boomy”, especially between 3200 and 4000 RPM. This can be clearly seen in the 3D order spectral map in Figure 10, with order on the X-axis, amplitude in dB(A) on the Y-axis and RPM, between 1000 and 5000, on the Z-axis.

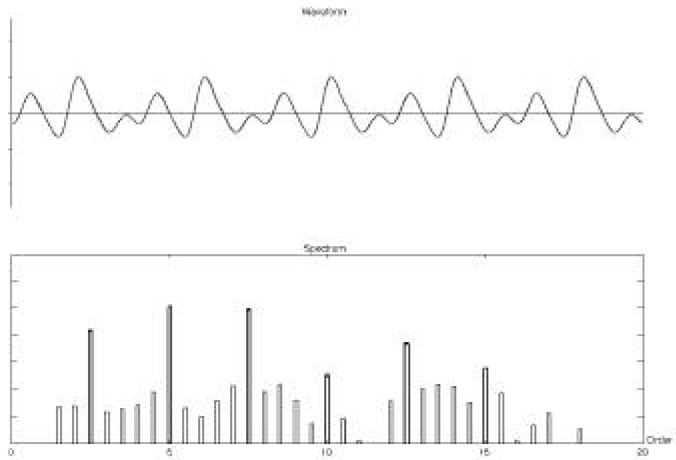

Figure 9. Binaural data at idle for baseline: Average time cycle (top) and corresponding order spectra (bottom).

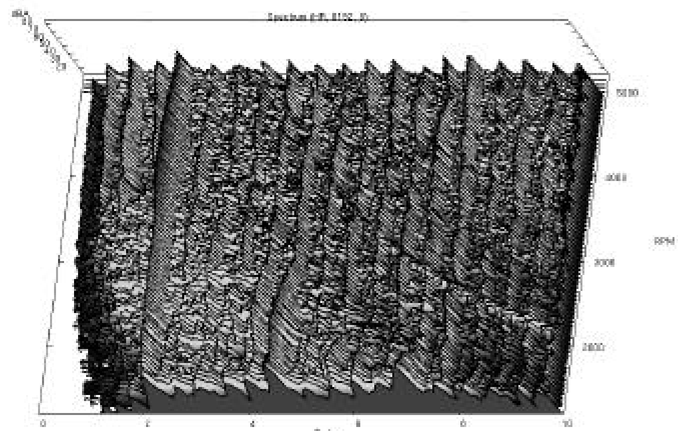

Figure 10. 3D order spectral map for runup in neutral.

In a more realistic loaded condition, such as a drive-away with moderate throttle opening, the 5.0 and 7.5 orders also contribute along with the 2.5. The spectrogram in Figure 11 shows the noise measured in this condition, with the three main orders represented by the diagonal lines of lighter color, from idle to the 3rd gear shift. The overall perception in this case is that of a “rougher” sound, due to the presence of these non-integer orders whose spacing increases from about 50 Hz to 130 Hz.

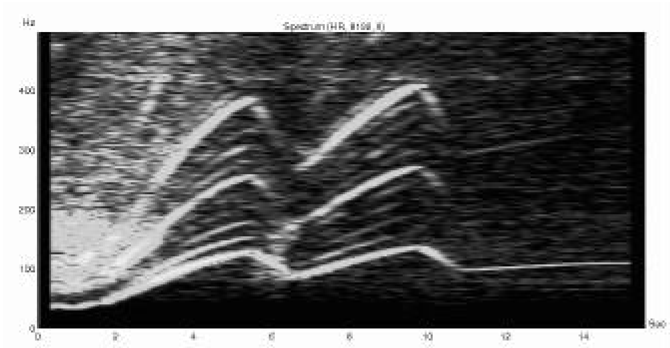

Figure 11. Spectrogram of measured noise of baseline system: Drive-away with moderate throttle opening

LISTENING TO THE MODEL

The WAVE model of the baseline system, once validated, was then applied to:

- Predict the orders of the baseline system at the position of the binaural head. This output was then used as a validation step to compare the sound quality of the model to that of the real noise.
- Model the proposed change to the exhaust system and predict the radiated noise orders. Figure 12 shows the comparison between baseline model and modification model for the overall tailpipe noise, as well as for the main orders. This output was then used to create the "virtual" tailpipe noise ("designed" muffler mounted on the "real" vehicle).

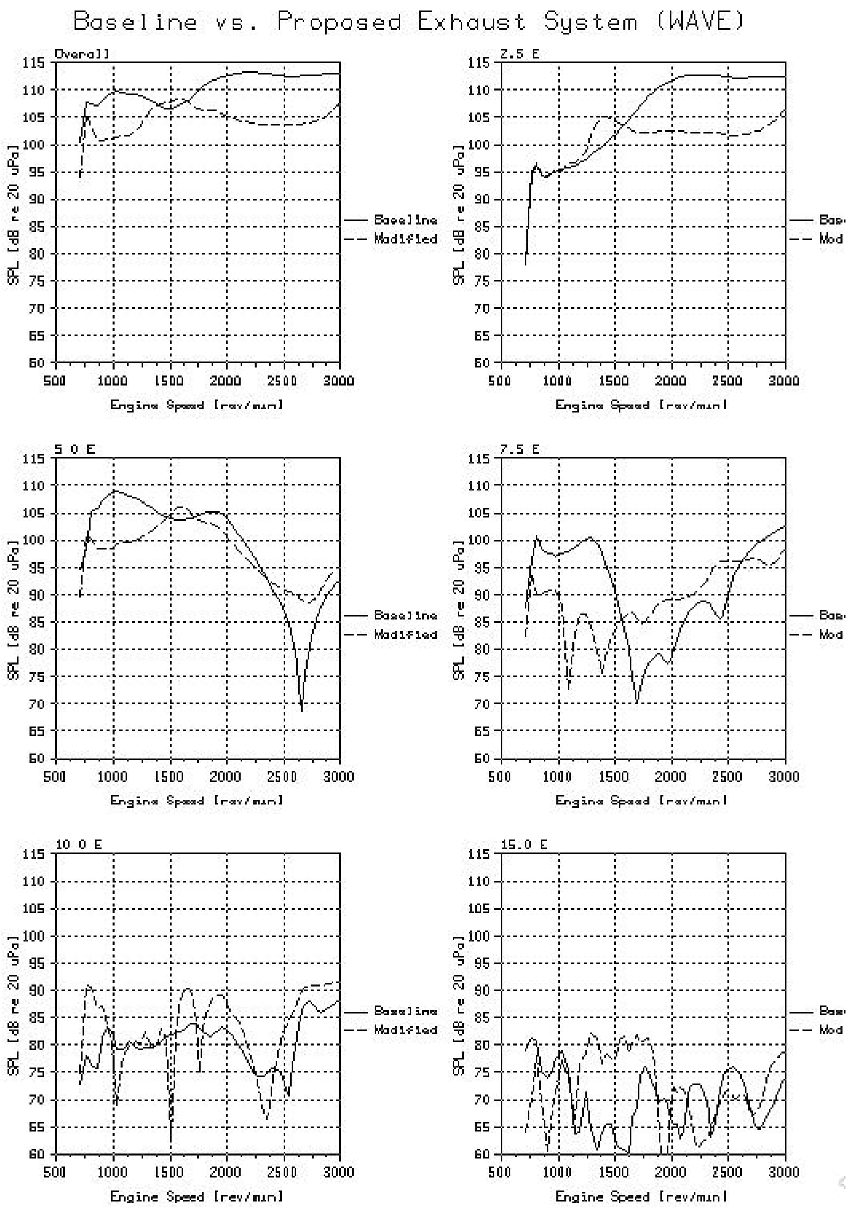

Figure 12. Comparison of predicted tailpipe noise for production system and for proposed modification

There are three possible ways of listening to the output of WAVE:

1. Direct play-back of the AIFF files as result from a run of WAVE
2. Play-back of WAVE AIFF files with synthesized background noise
3. Playback of WAVE AIFF files with measured background noise.

These different approaches will be discussed in detail in the following section

DIRECT PLAY-BACK OF WAVE AIFF FILES

In the simplest case, the user can listen to the output time history computed by WAVE. This method may be acceptable for sound quality specialists or product design and development engineers who can appreciate the slightest change in the sound of their product. In general, however, it is not adequate for less specialized engineers or for a panel of jurors representing the general customer since the predicted sound files only contain engine orders and lack a realistic sound quality.

During the presentation, the time histories with the measured and the predicted orders will be played back and compared to the overall measured noise.

PLAY-BACK OF WAVE AIFF FILES MIXED WITH SYNTHESIZED BACKGROUND NOISE

This technique can be successful when applied to tailpipe noise mainly because of the relatively simple structure of the sound field at the tailpipe. Tailpipe noise is basically made of two components: engine orders and “background” noise. At low to medium engine speeds, the engine orders are dominant (up to 20-30 dB above everything else), at medium to high speeds, the background noise (due to flow noise) dominates. Near the tailpipe, there is generally little noise contribution from other automotive components and the tailpipe can be well approximated by a monopole source.

If a database of recorded tailpipe sounds is available, a somewhat realistic background noise can be synthesized which resembles, in amplitude and frequency content, existing data from similar vehicles or exhaust configurations. The synthesized background can be generated with the exact slew rate of the WAVE prediction, so that the two time histories can be directly summed. This method fails of course when the relative difference in amplitude of the two files gets smaller and the relative phase starts to play a role.

During the presentation, an example of background noise, similar to the measured one, will be mixed with both predicted and measured orders and the results compared to the measured noise.

PLAY-BACK OF WAVE AIFF FILES WITH A MEASURED BACKGROUND NOISE

If recordings are available, digital filters can be used to simulate “what if” scenarios by mixing predicted engine orders to real background noise. In a previous paper, an example of digital filtering was presented in which the predicted insertion loss of a designed muffler was applied as a frequency based filter to the baseline noise recorded at the tailpipe. This filter operation was a convolution of the insertion loss (frequency domain function) with the whole recorded time history. This was possible since the muffler changes were after the Y-pipe and did not affect the noise order content. In this case the muffler can be assumed to work as a frequency-based filter. Additionally, since the insertion loss is a frequency domain function, it could be applied regardless of the slew rate of the runup.

This assumption is not valid in the case of the Viper, since the asymmetry of the modified exhaust would change the exhaust noise order and the predicted insertion loss of the proposed muffler would be different for different orders. An alternative methodology was then applied which is based on the capability of extracting and filtering the individual orders and then mixing the predicted noise orders with the unchanged background noise.

The procedure is as follows:

- The orders which most affect the overall sound quality perception (as an example, the 2.5 order during the neutral runup as in Figure 13) are removed from the original recording and stored as time histories in separate files. This can be done in several different ways as detailed in the next sub-section.

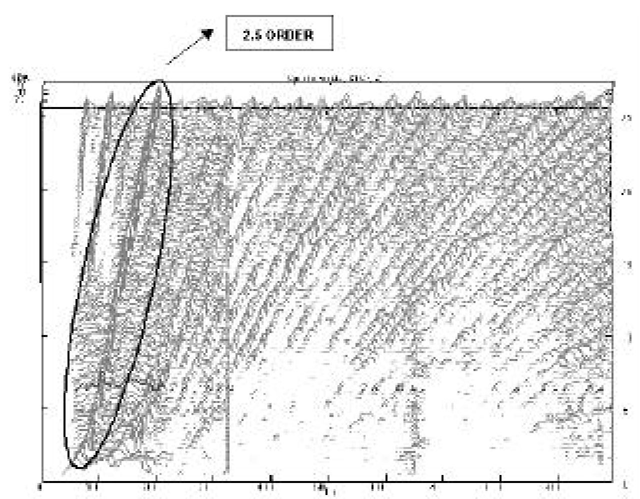

Figure 13. Binaural recording of tailpipe noise of production system. Runup in neutral

Figure 14 below shows the 3D spectra waterfall of the time history of the 2.5 order removed from the original.

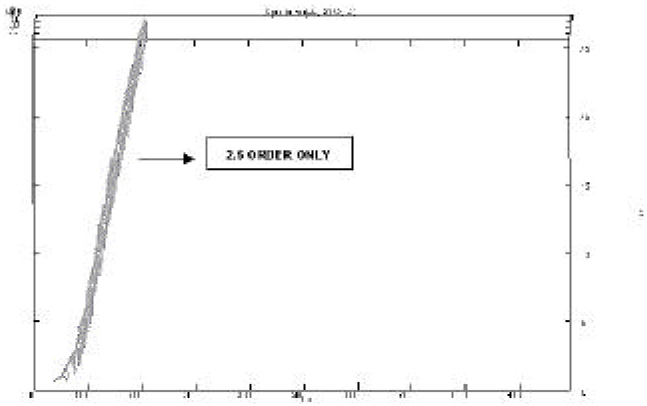

Figure 14. 3D spectral map of time history of 2.5 order (as extracted from original recording of runup in neutral)

- There are therefore two sets of time histories of engine orders: the predicted ones (output of WAVE) and the measured ones (extracted from recordings). For each order, the order profile versus frequency is computed for both predicted and measured (Figure 15 shows the frequency profile of the measured 2.5 order during neutral runup).

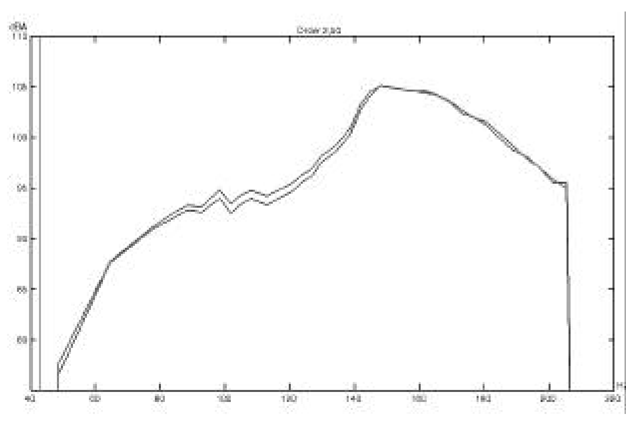

Figure 15. Profile of measured 2.5 order versus frequency (left and right ear of binaural head)

- A frequency domain filter is generated as ratio between the predicted order profile and the measured order profile. There will therefore be a filter for each order

$$Filter_N(f) = \frac{Predicted_N(f)}{Measured_N(f)} \qquad (1)$$

where N is the order number.

- For each order, the filter function is then applied as a FIR filter to the time history of the measured order:

$$Pred_N{}'(t) = Filter_N(f) \otimes Measured_N(t) \qquad (2)$$

where $Pred'_N(t)$ is the time history, synchronous with the measured noise, with the same frequency spectrum of the predicted order (Figure 16).

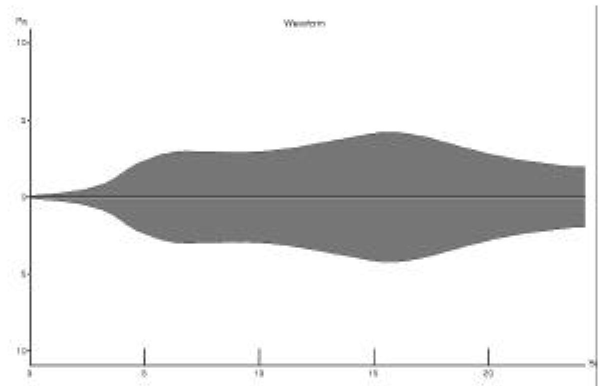

Figure 16. Time history of modified 2.5 order

- The new time histories of the modified orders can then be added back to the measured background noise.

This technique was validated by using a synthesized swept sine as a target for a single order, then by applying the procedure described above to that order and comparing the modified order to the (known) target. The modified order overlaps almost perfectly with the target order, as shown in Figure 17.

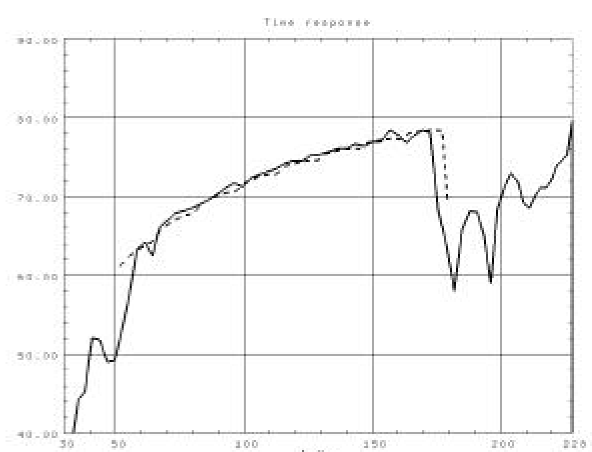

Figure 17. Profiles of swept sine (dashed) and modified order (solid) – Validation of the procedure

Obviously the same procedure can be applied to generate a specification for the exhaust designer. If, for example, the sound quality of a baseline exhaust system needs to be improved and a better sound quality is achieved by modifying the profile of the orders, the ratio between the modified and the baseline orders becomes the target insertion loss for the exhaust designer.

Depending on the test conditions, alternative techniques can be used to extract and/or remove the orders from a recorded signature. In the following sub-section, a brief discussion of these techniques is outlined.

Order Extraction Techniques

Three different techniques were used by the authors:

- Standard synchronous time averaging techniques
- IIR order tracking filters
- Vold-Kalman filters

Synchronous time averaging was applied to extract the engine orders from all steady state recordings.

IIR (Infinite Impulse Response) order tracked filters were applied both to extract and to remove orders from the measured noise [6]. The main advantage for using IIR filters is that the computation is fast. The main disadvantages are possible phase distortion and the lack of a phase reference, i.e., in the case of a notch filter, it removes everything within the specified bandwidth. Previous papers show how this may lead to significant errors in the estimation of the individual contributions. particularly in cases where multiple components may contribute to the noise in the same frequency range[7]. Examples of this phenomena are more often found when dealing with interior noise problems. During an engine speed sweep, engine orders can get very close or cross other components' orders and their resulting amplitude be affected by the interaction with the other component. This is not generally the case with tailpipe noise. However, since the relative phase among dominant orders affects the perceived modulation, it is important to preserve as much as possible the original phase.

Vold-Kalman filtering tools represent an optimized implementation of Kalman filters. Kalman filtering methods allow for the extraction of harmonic multiples of a known fundamental rotating frequency. In practice, Kalman filters for harmonic extraction determine the magnitude and phase of a locally stationary sinusoidal component having a known frequency variation. Therefore a Kalman filter only removes the content within the specified bandwidth which is synchronous with the reference signal (a tachometer in automotive applications). The main advantages for the application within this project are the phase reference to the tachometer and the capability of tracking high slew rate (particularly useful in wide open throttle acceleration, drive-aways and free-kicks).

CONCLUSIONS

The subjective evaluation of the predicted sounds has been completed for the steady state recordings and for the runup in neutral condition.

The main conclusions reached so far are:

1. The model represents fairly well the main engine orders (2.5, 5 and 7.5). If measured and predicted data are low-pass filtered with a cut-off around the 12.5 order , the subjective comparison between measured and predicted sounds is good. However, in certain conditions, such as steady state and no load, the model seems to overestimate the levels of the higher orders. In the measured noise, the higher orders do not contribute to the overall loudness, however they affect the perceived roughness of the sound. Therefore, if the frequency bandwidth of measured and predicted sounds is broadened to include these, a difference can be clearly perceived. This is possibly due to the absence of sound absorptive materials in the model (the Viper mufflers are packed with glass wool). Work is currently in progress at Ricardo to develop such a model to estimate the additional insertion loss due to the sound absorption material.

2. The direct play-back of the noise files generated by WAVE does not sound realistic enough to be used for a general, non-specialized audience. However, it can be used by exhaust design or development engineers when they need to assess the relative sound quality of different designs. More realistic "sound quality" is provided by mixing the predicted orders with synthesized background. This technique could probably be used, even with a non-specialized audience, for comparative sound quality assessment. Yet, it does not provide enough realistic quality to be used to replace a listening session of the real vehicle. The best quality of reproduction is achieved by mixing together measured and predicted time histories and by applying digital filtering techniques described in the main part of the paper. With this approach the resulting sounds can be played back to non-technical jurors for an overall assessment of sound quality features (too sporty or not sporty enough, too quiet, etc.).

Current investigation is focused on improving the model and its representation of the real muffler in a broader frequency range. Future investigations will focus more on the application of the sound synthesis techniques to different slew rates and to realistic drive-away conditions.

ACKNOWLEDGMENTS

The authors would like to thank Mr. Peter Kinsler of DaimlerChrysler Corp. for releasing proprietary information indispensable to the successful completion of this project and Dr. Havard Vold, of Vold Solutions, for providing his optimized implementation of Kalman filters to Tenneco Automotive.

REFERENCES

1. P. Hetherington, W. Hill, “An Analytical/Empirical Approach to Sound Quality Evaluation of Exhaust Systems”, SAE 971872, SAE Noise and Vibration Conference, Traverse City, MI, 1997
2. K. S. Peat, “LAMPS Software for the Acoustical Analysis of Silencers”, Proceedings of EuroNoise 1995 Conference, Lyon, France, Vol. 3, pp. 791-796
3. G. Cerrato, A. Crewe, R. Williams, “Sound Quality Tools for NVH Design”, Sound&Vibration, May 1997
4. Ricardo Software: WAVE Manual, Documentation/User’s Manual, version 3.4 – October 1996
5. MTS Sound Quality Engineering Users’ Manual, Version 3.5 – February 1998
6. E. C. Ifeachor, B. W. Jervis, “Digital Signal Processing – A Practical Approach”, Addison Wesley, 1993
7. H. Vold, J. Deel, “Vold-Kalman Order Tracking: New Methods for Vehicle Sound Quality and Drive-Train NVH Applications”, SAE 972033, SAE Noise and Vibration Conference, Traverse City, MI, 1997

DEFINITIONS, ACRONYMS, ABBREVIATIONS

Insertion Loss (IL):
Insertion Loss is defined as the difference between the acoustic power radiated without any filter and that with a filter which, in dB, translates into the following formula:

$$IL = L_{W_1} - L_{W_2} = 10\log(W_1 / W_2)$$

IIR and FIR Filters:
Infinite Impulse Response (IIR) and Finite Impulse Response (FIR) are the two broad classes in which digital filters are divided. Either type of filter can be represented by its impulse response sequence, which has a finite number of terms for the FIR filter and a infinite number of terms for the IIR filter.