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ON EXTRACTION OF IC-ENGINE INTAKE ACOUSTIC SOURCE DATA FROM NON-LINEAR SIMULATIONS

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Abstract

Non linear 1-D CFD time domain prediction codes are used for calculation of performance of the gas exchange process for IC-engines. These codes give time varying pressures and velocities in the exhaust and intake system. They could therefore in principle be used to predict radiated orifice noise. The accuracy is however not sufficient for using them as a virtual design tool. Using linear three dimensional frequency domain codes, more accurate results might be provided for complicated geometries. Radiated shell noise and frequency dependent damping could also be included in the frequency domain models. To calculate insertion loss of air-cleaner systems or the level of radiated intake orifice and shell noise, information about the engine as an acoustic source is needed. The source model used in the low frequency plane wave range for simulation of dominating engine harmonics is the linear time invariant 1-port model. The acoustic source data is usually obtained from experimental tests where the multi-load methods and especially the two-load method are most commonly used. These tests are time consuming, expensive and require physical hardware and can therefore not be used for early predictions. It would therefore be of interest to extract the acoustic source data from existing 1-D CFD gas exchange codes. This paper presents a comparison between results obtained applying the two-load technique to measurements on a six-cylinder personal car petrol engine and to 1-D simulations of identical intake systems on the same engine. The results show that it is possible to obtain reasonably accurate source strength as well as source impedance estimates for the intake side from 1-D gas exchange simulations.

INTRODUCTION

One-dimensional CFD-codes such as AVL-BOOST, Ricardo-WAVE and GT-Power are used within the automotive industry for IC-engine gas exchange studies. Except for performance quantities such as volumetric efficiency, torque and power they can provide unsteady pressures and flow velocities at different intake and exhaust system sections. Some of the codes also provide the ability to predict orifice noise using calculated velocity and a monopole assumption. The accuracy is however not overwhelming neither in absolute level nor resonance frequency caption. Some of the reasons for this might be the monopole assumption, the pressure boundary condition at the orifice in the non-linear solution or just the fact that the geometry of the air-cleaners and dirty air ducts are not transferable to 1-D. Using linear three dimensional frequency domain codes to describe the sound transmission in the air-cleaner, the dirty air duct and for the orifice sound radiation might be a way to improve the accuracy. To be able to calculate orifice noise and insertion loss as well as radiated shell noise using those codes, information about the engine as an acoustic source is needed. The objective of the work presented here is to study if such source data can be extracted from 1-D CFD simulations. This idea is not completely new, it has been attempted in [1] without success and in [4] with reasonable accuracy. The later work concerned however an exhaust system for a turbo charged truck diesel engine while this study deals with the intake side of a naturally aspirated personal car petrol engine with an intake manifold tuned to support pulse charging.

LINEAR TIME-INVARIANT SOURCE MODEL

If only plane waves are considered in the duct connecting the air cleaner to the intake manifold the most simple model which can be used to describe the engine as an acoustic source is the linear time-invariant frequency domain one-port model, see Figure 1. Here p_s represents the source pressure, ζ_s is the normalised source impedance, ζ_r is the normalised load impedance, q and p are the acoustic volume flow and acoustic pressure respectively at the source cross section. To get the impedances with dimension they have to be multiplied by the characteristic impedance $Z_0 = \rho_0 c / S$ where ρ_0 is the density for the undisturbed fluid, c is the speed of sound and S is the cross sectional area of the duct at the source cross section. At the source cross section the following equation is valid:

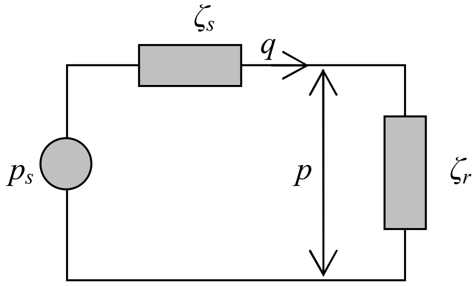

Figure 1: The linear time-invariant one-port source model

$$p_s \zeta_r - p\zeta_s = p\zeta_r \qquad (1)$$

This equation has two complex unknown, p_s and ζ_s, and can be solved by applying two complex equations, if it is assumed that the unknown variables are independent of the acoustic load. If more than two acoustic loads are applied an over-determined system of equations arises which can be used to reduce effects from deviation from source linearity and measurement errors. This is basis for the so-called Two-load method [2,3] for extracting the source data.

It is also of interest to get a check of to what degree the source deviates from linearity. For this purpose a linearity test, proposed by Bodén and Albertsson [5], similar to the coherence function is used. If a problem with m complex unknown is assumed and n measurements is performed an over determined equation system can be written as

$$\mathbf{A} \cdot \mathbf{x} = \mathbf{b} \tag{2}$$

where $\mathbf{A}$ is an $n \times m$ matrix, $\mathbf{x}$ an $m \times 1$ vector and $\mathbf{b}$ an $n \times 1$ vector. The used linearity coefficient is defined as

$$\gamma_c^2 = \mathbf{x}^{-1} \cdot \mathbf{x} = \mathbf{b}^{-1} \cdot \mathbf{A} \cdot \mathbf{A}^{-1} \cdot \mathbf{b}, \tag{3}$$

where $\mathbf{A}^{-1}$ is interpreted as the pseudo-inverse of $\mathbf{A}$. This linearity coefficient will have a value in the in the interval $0 \le \gamma_c^2 \le 1$, where the upper limit represents a perfect linear relationship.

TEST CASES

The engine used in the test set up was a 6 cylinder petrol engine. Acoustic pressures were measured in a straight duct at three positions situated 415, 535 and 1215 mm upstream the throttle. The acoustic (load) impedances were evaluated, using wave decomposition of the information from the three microphones. In the numerical non-linear simulation the acoustic pressures and velocities were extracted at a position 402.5 mm from the throttle and transferred, using the 4-pole matrix for a straight duct with flow, upstream to match the measurement evaluation section. The numerical acoustic (load) impedances were obtained directly by Fourier transformation of the unsteady pressures and velocities.

Measurements and simulations were made for six different acoustic loads using the same intake system where a variable length quarter wave resonator was connected to the clean air duct, 1500 mm upstream the throttle. The six different lengths for the quarter wave resonator were: 0, 380, 635, 985, 1430 and 1910 mm. To capture the behavior of an engine run-up a large number of operation points were measured. The engine was held at steady state operating conditions and the pressures were measured at 1700 rpm and at every 100 rpm between 2000 and 3700 rpm at full load (WOT).

RESULTS AND DISCUSSION

A personal car petrol engine is normally operated at an engine speed somewhere between 600 and 6500 rpm with maximum torque output somewhere between 3000 and 5000 rpm when naturally aspirated. For a typical truck engine the corresponding figures would be 500 to 2100 rpm with maximum torque output at 1200 rpm. For the personal car petrol engine the ability to predict a wider engine speed range with good resolution is evident. The measurements and simulations in this investigation are made at steady state conditions and the results will not be the same as from a slow transient run-up. However the character of the results will be similar. Also worth commenting is the fact that just full load conditions are studied. This choice is made upon the fact that the flow through the throttle is choked during a wide range of part load conditions and therefore no sound transmission is possible. At the moment drive-by legislation where intake noise is one of the main contributors is based on full load conditions.

To verify the confidence level of the calculations, the calculated source pressure and impedance are compared to measured data. Concerning the overall level of the source pressure, which is shown in Figure 2, a good agreement is achieved for absolute level as well as character. However the overall level is highly influenced by the 3rd engine order and is almost just an offset. The confidence level of the third order source pressure level is good as well. Worth noticing is that the source pressure is not constant but depends strongly on the engine speed.

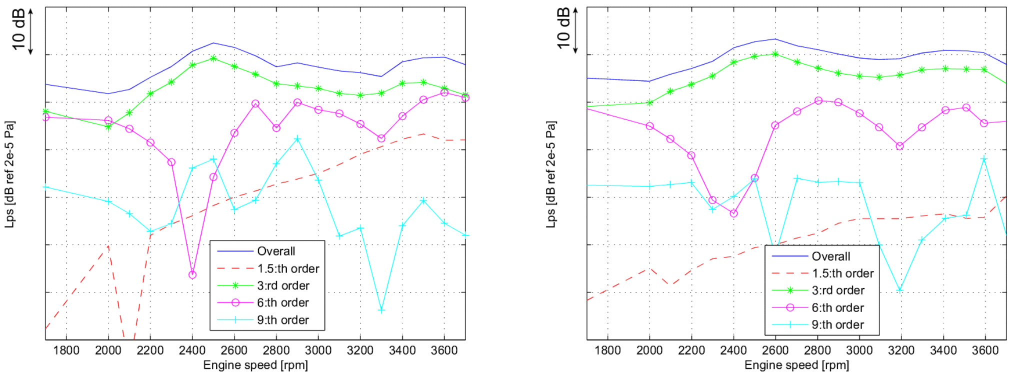

Figure 2: Source strength obtained from measurements (left) and WAVE calculations (right) using all six acoustic loads. Overall level is a sum of first 32 half orders.

Source data for the 3rd engine order is shown in Figure 3. This is the main order upstream the throttle since lower orders are more or less cancelled depending on the level of symmetry in the intake manifold. The wave model over-predicts the source pressure level by about 5 dB which indeed is a good result since the calculated curve is almost an offset of the measured. Worth noticing is that when the simulated values leaves the 5 dB offset and approaches the measured curve at 2500 rpm, the source impedance behaves almost as at a resonance. The real part shows a strong peak while the imaginary part is switching from positive to negative. The conclusion from this might be that the calculated amplitude of the source pressure is to high except at the peak at 2500 rpm where the losses are too low. Moving the source data section upstream, results in a shift of the peak downwards in frequency, while an extension of the clean air duct leaves the peak frequency unaffected. This shows that the peak frequency is a geometrical property of the source. The level of linearity is excellent in both measurements and calculations

The confidence of the 6^{th} engine source data can be judged in Figure 4. The source pressure is quite good except at 2400 and 2800 rpm, this time noticing a corresponding smaller deviation from unity in the linearity measure. At 2400 and 2500 rpm the real part of the source impedance is also unphysical negative. This behavior might be caused by a weak 6^{th} order source pressure corresponding with a strong 3^{rd} order resulting in non-linear effects.

The 9^{th} engine order is less accurate than order 3 and 6 with a maximum deviation of approximately 10 dB. The character of the curves is not good but similarities are definitely present. The source impedance is fairly good except at the peaks which the calculations seem to underestimate. It is important to note that the linearity measure for the measurements is below 0.6 at some rpm's which might explain some of the discrepancies.

In Figure 6 the 1.5^{th} order source data is shown. The character of the source pressure is reasonable but the level is not good. This is not surprising since the wave-model at the moment is not aiming to simulate cylinder to cylinder variation which might be a big source of a high 1.5^{th} order level. The 1.5^{th} order is also more affected by measurement deviations since the calibration between the microphones resulted in less good accuracy below 300 Hz. The imaginary part of the 1.5^{th} order impedance shows good agreement while the real part is not very good; however it is positive at almost the same rpm's. The linearity of the 1.5^{th} order is very good for the measurements as well as for the calculations.

Finally the results from all six acoustic load cases where used for further studies of how well measured pressures can be predicted. Figure 7 shows comparisons between measured/calculated pressures at the load case 3 with a 635 mm quarter wave resonator and pressures that have been predicted from the measured/calculated impedance and the source data from the five other acoustic loads. Both the calculated as well as the measured data predicts the unsteady pressures well. The agreement between measured and calculated pressures is also good except for the 1.5^{th} order which was already noticed in the comparison of the source data.

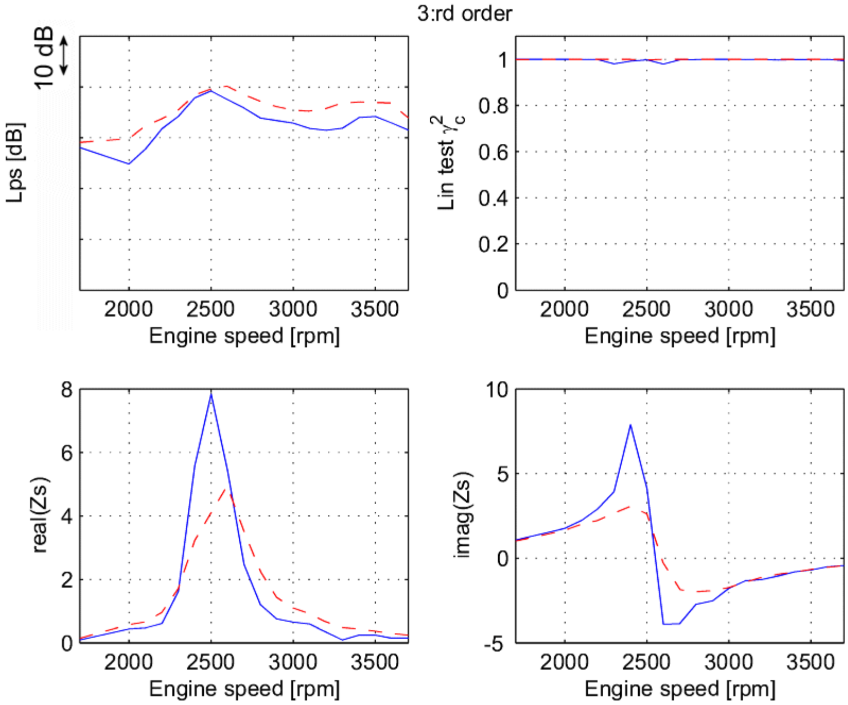

Figure 3: Source data obtained from measurements (solid line) and WAVE calculations (dashed line) for 3[rd] engine order.

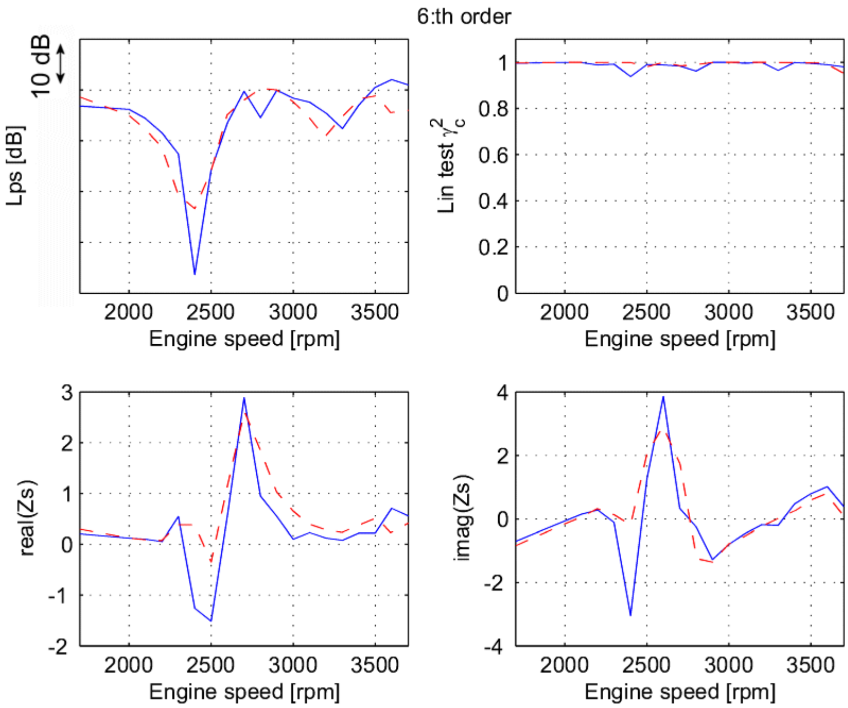

Figure 4: Source data obtained from measurements (solid line) and WAVE calculations (dashed line) for 6[th] engine order.

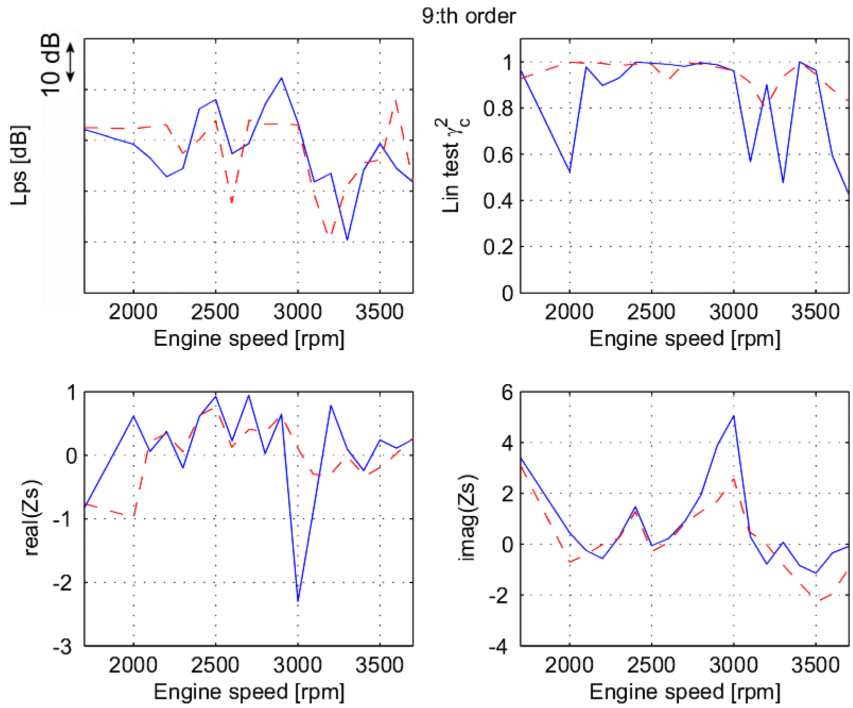

Figure 5: Source data obtained from measurements (solid line) and WAVE calculations (dashed line) for 9th engine order.

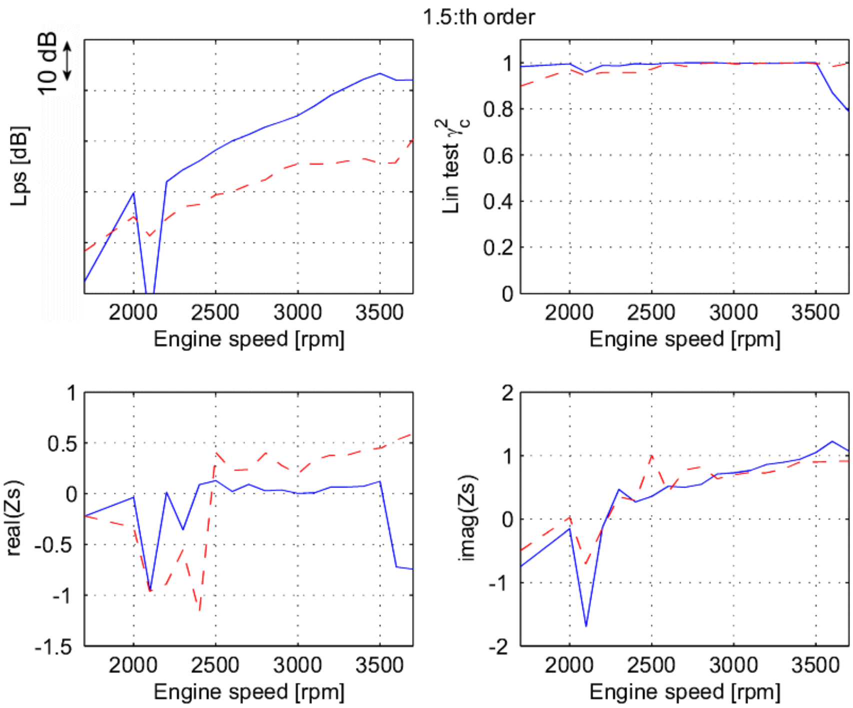

Figure 6: Source data obtained from measurements (solid line) and WAVE calculations (dashed line) for 1.5th engine order.

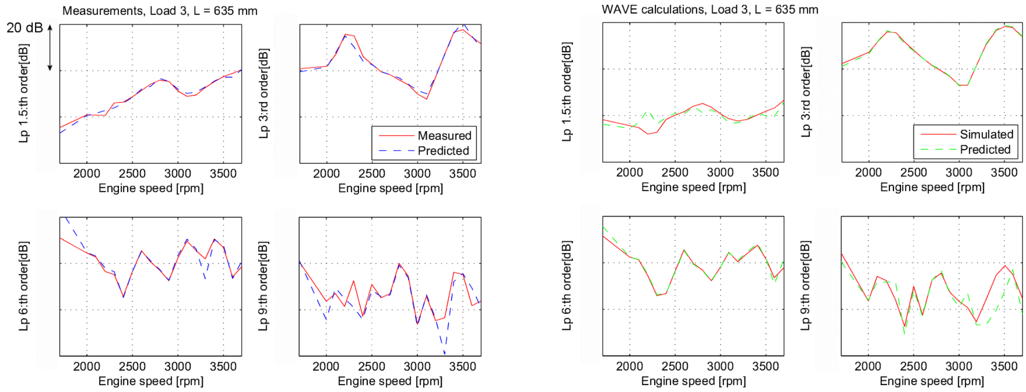

Figure 7: Sound pressure level at source section: Measured and predicted spl obtained from measurements (left), calculated and predicted spl obtained from WAVE calculations (right) using five acoustic loads.

CONCLUSIONS

The possibility to extract linear acoustic source data, needed for linear three dimensional frequency domain sound propagation codes, from 1-D CFD gas exchange simulations using Ricardo-WAVE has been tested. The simulated source data for a 6-cylinder petrol engine provides reasonably accurate results when predicting fluctuating pressure in the intake system, especially for lower engine orders. This therefore seems to be a promising technique which could replace expensive, and time consuming experimental source data determination.

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