

# Determination of the acoustical impedance of an internal combustion engine exhaust.

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## Abstract

The acoustical impedance of the exhaust of an internal combustion engine is measured using the two microphone transfer function method according to ISO/FDIS 10534-2. Some improvements are proposed to this procedure. The engine exhaust impedance is also simulated using electrical analog circuits, wherein geometrical data of the engine and the manifold is used. The simulation results correlates well with the measurement results. Some special cases are simulated, to determine the engine components which contribute primarily to its acoustical impedance.

## 1 Introduction.

In the design process of exhaust systems, the internal combustion engine plays a primary role. In many theoretical considerations of exhaust systems, wherein usually the source impedance will be neglected, or characterized as a pressure source (zero impedance), non-reflective source ( $\rho c$  impedance) or volume velocity source (infinite impedance), the discrepancies between the predicted and the measured exhaust system performance demonstrates that none of these assumed source impedances is correct. The knowledge of the acoustical engine impedance is essential.

## 2 Measuring acoustical impedance.

The two microphone transfer function method is used to determine the acoustic impedance of a combustion engine exhaust. The method is based on the draft international standard ISO/FDIS 10534-2. The setup is schematically presented in figure 1. The electrical equivalent circuit [1] is presented in figure 2.

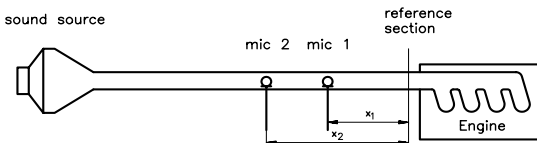


figure 1: Scheme of an acoustical impedance measurement setup using the two microphone transfer function method, wherein the engine has the unknown impedance  $Z_l$ .

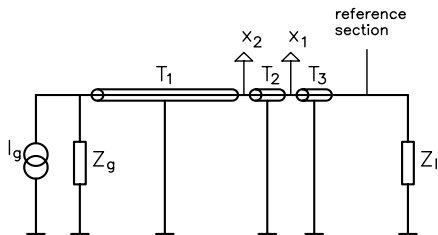


figure 2: Electrical analog circuit of an acoustical impedance measurement setup using the two microphone transfer function method.

The method uses the transfer function  $T_{12}$  measured between the two microphones positioned at  $x_1$  and  $x_2$  on the waveguide connected to the impedance to be measured. Using one-dimensional wave theory [2], the reflection coefficient  $\Gamma_l$  at the load equals

$$(1) \quad \Gamma_l = -\frac{e^{j\omega t_1} - T_{12} e^{j\omega t_2}}{e^{-j\omega t_1} - T_{12} e^{-j\omega t_2}}$$

wherein  $t_1$  and  $t_2$  are the traveling times of the acoustic wave between the microphone positions  $x_1$  and  $x_2$  to the reference section respectively. They can be measured by closing the duct at the reference section. The traveling times are

$$(2) \quad t_1 = \frac{1}{4f_1} \quad \text{and} \quad t_2 = \frac{1}{4f_2}$$

The frequencies  $f_1$  and  $f_2$  correspond to the quarter wavelength between the closed end and the positions  $x_1$  and  $x_2$  respectively. Figure 3L presents the measurement of the transfer function  $T_{12}$  with the duct closed. In this case,  $f_1 = 247$  Hz and  $f_2 = 125$  Hz. The corresponding traveling times are  $t_1 = 1.0066$  ms and  $t_2 = 1.9870$  ms.

Corrections need to be made because the microphone responses are not identical. To measure these corrections, the microphones will be exchanged from position  $x_1$  to  $x_2$  and vice versa, without changing the electrical connections. Then, the transfer function between the microphones is measured again. This transfer function  $T_{21}$  must be the inverse of the transfer function  $T_{12}$ . Then, the correction factor  $\delta$  is a complex function of frequency and is calculated from

$$(3) \quad \delta^2 T_{12} T_{21} = 1$$

At last, the load impedance  $Z_l$  can be calculated from the reflection coefficient:

$$(4) \quad Z_l = Z_0 \frac{1 + \Gamma_l}{1 - \Gamma_l}$$

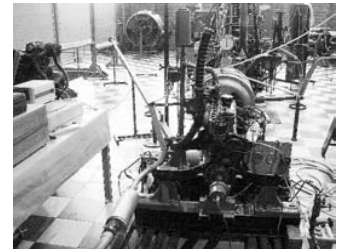
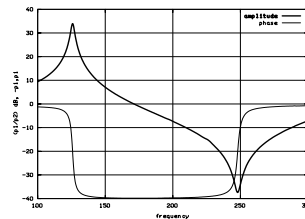


figure 3L: Calibration measurement using the closed duct, containing the first pole and first zero of the microphone transfer function.

figure 3R: Setup to measure the acoustical impedance of a 747 cm<sup>3</sup> combustion engine exhaust.

### 3 Measurement and simulation of the engine exhaust impedance.

The method is applied to measure the acoustical impedance of an engine. The scheme of the setup is shown in figure 1. A photograph of the setup is shown in figure 3R.

At the exhaust, the measurement duct is connected. The duct has a cross-section of 11.56 cm<sup>2</sup> and is 6 m long. The characteristic impedance equals 347 kΩ (1 Ω = 1 Pa s/m<sup>3</sup>). At the other end, a horn driver of 100 W electrical power is connected. The acoustical impedance of the sound source itself does not affect the measurement result.

The measurement method cannot distinguish between a reflected wave and a wave generated by the engine. The noise generated by the engine disturbs the reflection coefficient and therefore, it is minimized by running the crankshaft with an electric motor. The intake is sealed, then the engine cannot pump air from the intake to the exhaust.

The simulation is carried out using the electrical analog circuit presented in figure 4. The circuit is composed by analyzing the engine parts contributing to the acoustical impedance. The circuit components are determined using the geometrical data of the engine and the exhaust manifold.

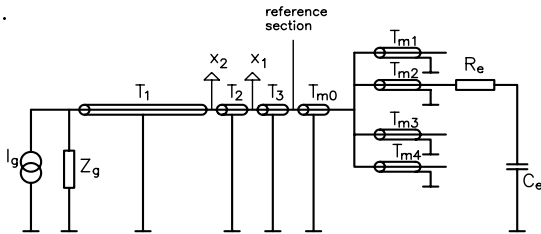


figure 4: Electrical analog circuit of an engine in the acoustical impedance setup from figure 1.

In this circuit, the transmission lines  $T_1$ ,  $T_2$  and  $T_3$  at the left of the reference section represent the measurement waveguide. The transfer function is taken between  $x_1$  and  $x_2$ . At the left end, a volume velocity source with its internal source impedance  $Z_g$  in parallel, generates the exciting volume velocity.

At the right side situates the equivalent circuit of the engine. The transmission lines  $T_{m0}$ ,  $T_{m1}$ ,  $T_{m2}$ ,  $T_{m3}$  and  $T_{m4}$  represent the manifold coupled to the engine cylinders, from which three are closed by the exhaust valves and one is open. The closed valves should have infinite resistance and are represented by a circuit interruption. At the open cylinder, the exhaust valve resistance  $R_e$  and the cylinder volume capacitor  $C_e$  is connected. The value of the capacitor corresponds to the volume of the cylinder, when the piston is in the middle position.

In figure 5L and 5 R, the real and imaginary part of the measured and simulated reflection coefficient in terms of frequency are represented respectively. Both functions exhibit a similar trajectory. The acoustical impedances, presented in figure 6L and 6 R, are calculated from the reflection coefficients presented in figure 5L and 5 R respectively. Also the simulated and the measured impedance match each other in good agreement. The 0 dB level corresponds to the characteristic impedance of the measurement waveguide. The phase ranges between +90° and -90°, i.e. the impedance ranges between inductive and capacitive.

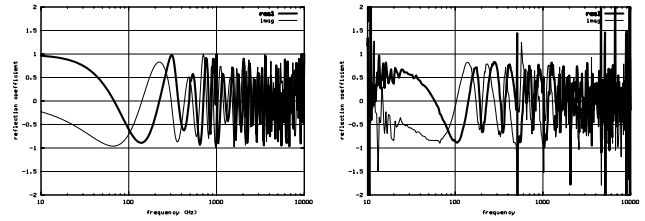


figure 5L: Simulated engine exhaust reflection coefficient from the electrical analog circuit presented in figure 4. figure 5R: Measured engine exhaust reflection coefficient.

The -20 dB/decade line below 150 Hz in the impedance function corresponds with the engine cylinder volume combined with the manifold volume. At 150 Hz, the acoustic mass inside the manifold vibrates on the cylinder volume and is damped by the exhaust valve resistance. The successive resonances are mainly internal manifold resonances. The "mean" impedance at higher frequencies becomes equal to the characteristic waveguide impedance. The engine impedance becomes anechoic at high frequencies.

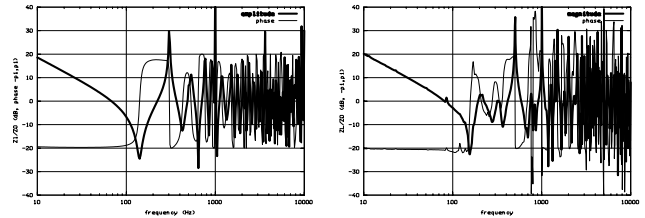


figure 6L: Simulated engine exhaust impedance from the electrical analog circuit presented in figure 4. figure 6R: Load impedance of the engine exhaust at 1000rpm. The picture is similar for 2000rpm.

Two extreme cases are simulated. Figure 7L presents the exhaust manifold impedance closed at all ports. Figure 7R presents the impedance with the measurement waveguide directly connected to the engine cylinder. Roughly, the engine only adds damping to the manifold impedance. The manifold is the primary contributor to the engine impedance.

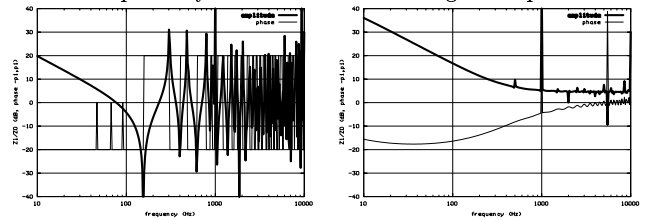


figure 7L: Simulated engine exhaust impedance with all four manifold ports closed by infinite resistances (open circuit). figure 7R: Simulated engine exhaust impedance with the measurement waveguide directly connected to the exhaust valves.

### 4 Conclusion.

A good agreement is observed between the measured and simulated impedances of an engine exhaust. Two extreme cases are simulated, indicating that the exhaust manifold contributes primarily to the engine acoustical impedance.

### References

- [1] Beranek L. L. "Acoustics", McGraw-Hill, 1954
- [2] Neff, Jr, H. P. "Basic Electromagnetic Fields", Harper & Row, 1987