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 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.

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.

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 international standard ISO 10534-2. The setup is schematically presented in figure 1. The electrical equivalent circuit is presented in figure 2.

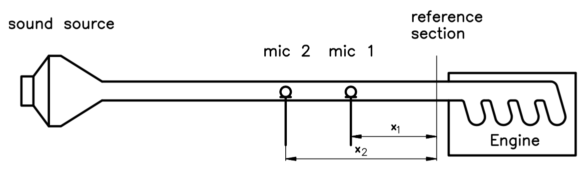

Figure 1: Scheme of an acoustical impedance measurement setup using the two microphone transfer function method, wherein the engine has the unknown impedance Z_l.

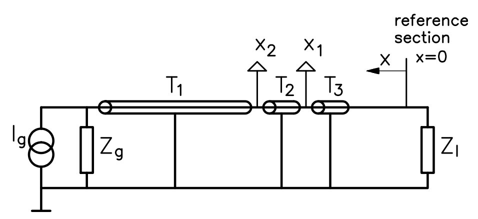

Figure 2: Electrical analog circuit of an acoustical impedance measurement setup using the two microphone transfer function method.

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, the reflection coefficient Γ_l at the load equals

$$\Gamma_l = -\frac{\mathrm{e}^{j\,\omega\,t_1} - T_{12}\,\mathrm{e}^{j\,\omega\,t_2}}{\mathrm{e}^{-j\,\omega\,t_1} - T_{12}\,\mathrm{e}^{-j\,\omega\,t_2}} \tag{1}$$

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

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

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 3 left 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 vise 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 δ is a complex function of frequency and is calculated from

$$\delta^2\, T_{12}\, T_{21} = 1 \tag{3}$$

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

$$Z_l = Z_0\,\frac{1 + \Gamma_l}{1 - \Gamma_l} \tag{4}$$

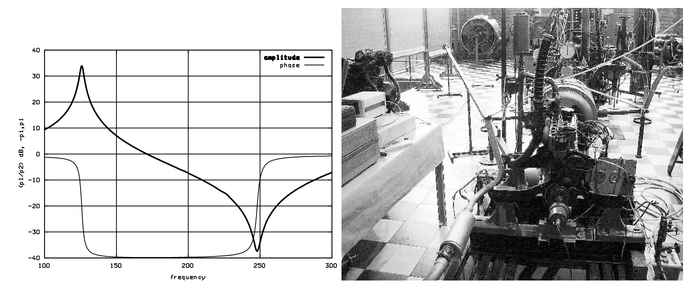

Figure 3: *left:* Calibration measurement using the closed duct, containing the first pole and first zero of the microphone transfer function. *right:* Setup to measure the acoustical impedance of a 747 cm^3 combustion engine exhaust.

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 3 right.

At the exhaust, the measurement duct is connected. The duct has a cross-section of 11.56 cm^2 and is 6 m long. The characteristic impedance equals 347 kΩ ($1\,\Omega = 1\,\mathrm{Pa\,s/m^3}$). 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.

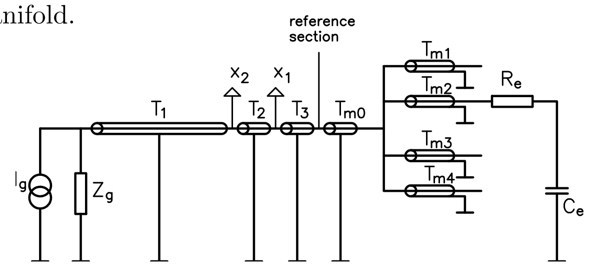

Figure 4: Electrical analog circuit of an engine in the acoustical impedance setup from figure 1.

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 5 left and 5 right, 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 6 left and 6 right, are calculated from the reflection coefficients presented in figure 5 left and 5 right respectively. Also the simulated and the measured

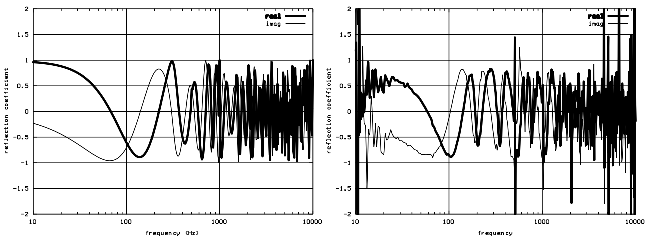

Figure 5: *left:* Simulated engine exhaust reflection coefficient from the electrical analog circuit presented in figure 4. *right:* Measured engine exhaust reflection coefficient.

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.

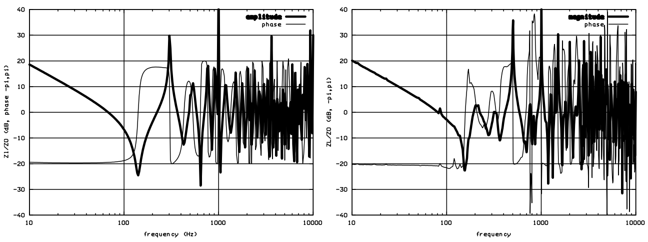

Figure 6: *left:* Simulated engine exhaust impedance from the electrical analog circuit presented in figure 4. *right:* Load impedance of the engine exhaust at 1000rpm. The picture is similar for 2000rpm.

Two extreme cases are simulated. Figure 7 left presents the exhaust manifold impedance closed at all ports. Figure 7 right 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.

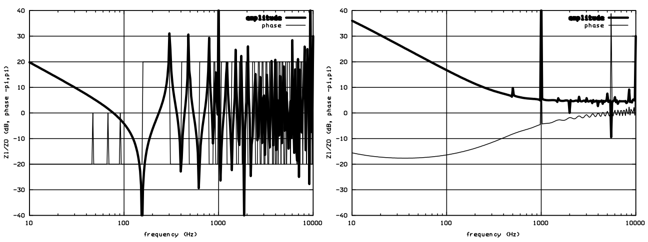

Figure 7: *left:* Simulated engine exhaust impedance with all four manifold ports closed by infinite resistances (open circuit). *right:* Simulated engine exhaust impedance with the measurement waveguide directly connected to the exhaust valves.

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] René Boonen, Paul Sas, Determination of the acoustical impedance of an internal combustion engine, proc. of the ISMA2002 conference, Leuven, Belgium, **5** (2002), 1939-1946 (*also available at* `www.isma-isaac.be`)