# Development of a cold engine simulator to carry out acoustic and fluid-dynamic experiments with exhaust systems.

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**Abstract**
*A cold engine simulator has been developed which generates realistic exhaust noise with the associated gas flow using compressed air. The device permits to carry out reliable experiments with new concepts of exhaust systems without taking precautions against the hot corrosive exhaust gases. The acoustic impedance and the source spectrum are evaluated and compared with a regular internal combustion engine and with simulation of electrical analog circuits. This comparison shows that the cold engine simulator has similar characteristics as the engine.*

## 1 Introduction.

During the development of engine exhaust systems, experiments on prototypes of exhaust systems are very difficult without a representative sound source. Testing on an internal combustion engine can destruct the valuable prototypes, if no precautions are taken against the hot corrosive exhaust gases. However, the acoustical circumstances on test setups like loudspeaker and fan setups differ very much of these of an engine. As consequence, the obtained results are often not reliable.

The exhaust noise is caused by discharges of the expanded gases in the engine cylinder into the exhaust line when the exhaust valve opens. The discharge time is such short, that the cylinder volume change due to the piston movement is negligible. It can be considered as a discharge of a constant volume. The developed cold engine simulator simulates this process using compressed air.

## 2 Cold engine simulator principle.

A scheme of the cold engine simulator is presented in figure 1. The device consists of a regular engine block whose pistons are fixed at the bottom dead point. At the intake, compressed air is supplied at the same pressure as the pressure level at the end of an engine expansion cycle. The camshaft is run electrically. Its speed can be set on a frequency converter. The result is a series of gas discharge pulses in the exhaust, which are very similar with the pulses of a regular engine. The presented cold engine simulator is built using a Volkswagen 1.6 l engine.

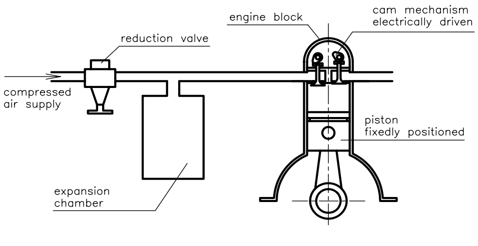

*figure 1:* Scheme of the cold engine simulator.

## 3 Exhaust acoustic impedance and source spectrum.

The acoustic impedance of the exhaust and the sound spectrum will be measured and compared with measurements on a real engine and with simulations of electrical analog circuits. The exhaust acoustic impedance is measured using the two microphone transfer function method [1] on the simulator and the regular engine. The sound power is measured directly after the exhaust manifold using a pressure sensor.

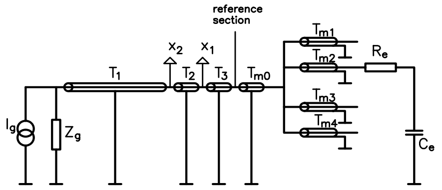

*figure 2:* Electrical analog circuit of an acoustical impedance measurement of an engine exhaust using the two microphone transfer function method.

Figure 2 represents the electrical analog circuit [1] of the acoustical impedance measurement of the engine exhaust. 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.

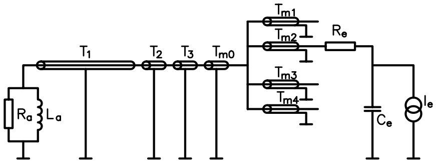

*figure 3:* Electrical analog circuit of an exhaust noise generating engine connected to an open duct.

Figure 3 presents the circuit to simulate the sound source. The waveguide is now open. This is represented by the resistor-inductor combination $R_a$ and $L_a$ which is the spherical radiator impedance. A volume velocity source $I_e$ is connected over the cylinder capacitor. The discharge pulse is in first instant approximated as a Dirac impulse, which spectrum is constant in terms of frequency. Consequently, the volume velocity source is constant in terms of frequency. The volume velocity is proportional to the amount of gas released by the engine. The sound spectrum is displayed between $T_3$ and $T_{m0}$.

Figure 4L shows a photograph of the measurement setup to determine the acoustical impedance of the cold engine simulator. At the front, the exciting loudspeaker is connected. Figure 4R shows the connection of the measurement waveguide to the cold engine simulator in more detail.

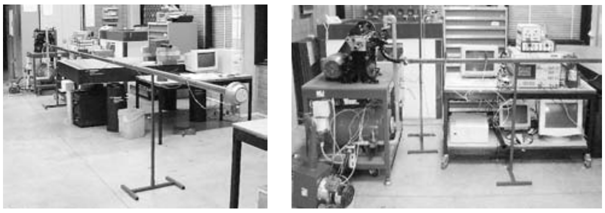

*figure 4L:* Measurement setup to determine the acoustical impedance of the cold engine simulator. *figure 4R:* The cold engine simulator connected to the measurement waveguide.

## 4 Results.

Figure 5L and 5R represents the exhaust acoustic impedance and the sound spectrum measurement of the cold engine simulator. The acoustical impedance resulting from simulation of the circuit presented in figure 2 is presented in figure 6L. The exhaust sound spectrum, resulting from simulation of the circuit presented in figure 3 is presented in figure 6R. At last, figure 7L represents the exhaust acoustic impedance of a 747 cm$^2$ Renault engine exhaust [1]. The sound spectrum measurement, represented in figure 7R, is carried out on a 1600 cm$^2$ Volkswagen engine.

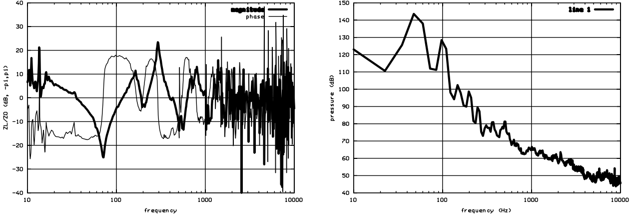

*figure 5L:* Measured acoustical impedance of the cold engine simulator exhaust, while running at 1000 rpm. *figure 5R:* Measured power spectrum of the manifold pressure on the cold engine simulator.

The −20 dB/decade line below 80 Hz in the impedance function, represented in figure 5L and 6L, corresponds with the engine cylinder volume combined with the manifold volume. At 80 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. The same trajectory is found for the Renault engine. The major difference is that the resonance of the acoustic mass in the manifold on the cylinder volume is shifted to 150 Hz. The engine cylinder and the exhaust manifold of the 747 cm$^2$ Renault engine is much smaller than these of the 1600 cm$^2$ Volkswagen engine, resulting in a higher impedance.

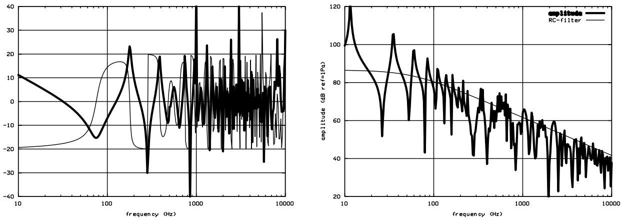

*figure 6L:* Simulated engine exhaust impedance from the electrical analog circuit presented in figure 2. *figure 6R:* Simulated engine exhaust sound spectrum from the electrical analog circuit presented in figure 3.

The simulated sound pressure in figure 6R contains the waveguide and the manifold resonances. The spectrum is carried on a base spectrum represented by the thin line. The base spectrum $p_{base}$ is a first order system given by

$$p_{base} = I_e \, \frac{Z_0}{1 + j\,\omega\,C_e\,(R_e + Z_0)} \tag{1}$$

wherein $Z_0$ equals the waveguide characteristic impedance. The other symbols are mentioned in figure 3. The source strength is strongly dependent on the engine components ($C_e$ and $R_e$) and the connected waveguide. The acoustical impedance of the connected waveguide appears solely in the numerator and dominates the produced sound pressure. The manifold has only minor influences, the dips in the pressure characteristic at 280 Hz, 400 Hz and 800 Hz are manifold effects. This baseline pressure is dominantly present in the source spectrum measurements presented in figure 5R and 7R. These are power spectra calculated from pressure measurements in time domain. The source spectrum of the cold engine simulator is similar to the combustion engine spectrum.