

Reduction of Exhaust Noise by Means of Thermal Acoustics

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ABSTRACT

It is well known that mufflers attenuate the engine noise essentially through dissipative and reflective effects. There is however another alternative technique for noise attenuation that has not been deeply explored, i.e. thermal acoustics. In fact the temperature of the gas influences the acoustic behaviour of the exhaust system; reducing the exhaust gas temperature, the sound pressure of the acoustic waves is reduced. This phenomenon could be used to improve the sound attenuation.

We propose an experimental study of this phenomenon and of how it could be used to reduce the exhaust noise. We measured that, using in underfloor position passive heat exchangers like corrugated pipes, the exhaust gas quickly exchanges heat with the external environment and arrives to the rear muffler significantly colder. We observe about 2 dB decrease of the OA dB value when the gas temperature decreases of about 100°C. With colder exhaust gas the noise can be heavily reduced; in particular the flow noise improves the sound attenuation at high engine speed.

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INTRODUCTION

It is well known that the noise produced by an internal combustion engine flowing through an exhaust system has two main components: a low frequency noise (below 800-1000 Hz), called generally "breathing noise", due to the periodical combustion process and to the consequent opening of the exhaust valves, and a high frequency noise (above 800-1000 Hz), called "flow noise", which is due to the jet noise (produced by the impact of the fast exhaust gas in the tail pipe with the external static air) and to the self-generated noise (due to the exhaust system discontinuity). This second component significantly increases with the engine speed because it is dependent by the flow speed. At high engine speed, the self-generated noise is predominant and it is normally controlled, for example, increasing the tail pipe section. [1]

Schematically, a standard modern exhaust system is composed by a manifold, a catalytic converter (that together are the "hot end"), a decoupling element, a long central pipe placed under the floor of the vehicle where a central muffler can be positioned, one or two mufflers and one or more tail pipes (that all together constitute the "cold end"). The cold end system taken in study (base version) is represented in [figure 1](#):

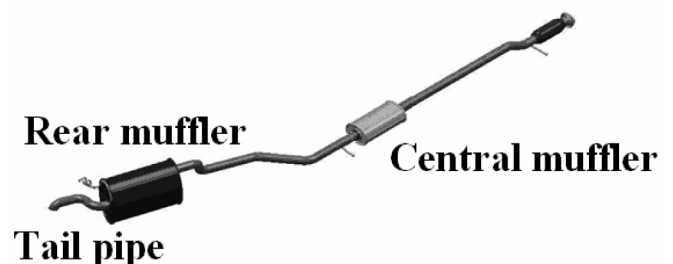


Figure 1. Cold end

In order to reduce the mentioned contributions to noise, mufflers based on dissipation and/or interference and/or reactive principles are used [2, 3, 4, 5, 6, 7]. In this paper we want to explore the limits of an alternative technique based on the cooling of the exhaust gas, i.e. thermal acoustics. A brief remind of it can be useful; in fact from the classical equation of the perfect gas:

$$P \cdot V = n \cdot R \cdot T \quad (1)$$

where P is the pressure of the gas, V the volume, n the mass quantity expressed in moles, R the perfect gas constant and T the absolute temperature.

It is easily notable that if we decrease the temperature of the gas we linearly decrease its volume (considering the pressure as a constant) and, doing that, we reduce the speed of the flow inside the exhaust system, hence reducing the friction between the pipe and the flow and consequently the flow noise.

Looking from another side, it has been observed that the jet noise is empirically proportional to about the fifth power of the flow speed [8]. Due to this, even a little reduction of the flow speed (obtained reducing the gas temperature), has the effect to strongly reduce the jet noise.

The simulation of noise as a coupling of acoustic and fluid-dynamics sciences is not actually a standard tool of commercial softwares; so to evaluate the self-generated noise hence it is more practical to follow a strictly experimental approach. In the cited paper of A.J. Green and P.N. Smith "Gas flow noise and pressure loss in heavy vehicle exhaust system" [8]. A semi-empiric formula is proposed for the calculation of the jet noise (also used in some commercial softwares):

$$L_w = E_w + 10\log(P_{at}*750) - 17.5\log(T) + 20\log(D) + 45\log(U) - 26.6 \quad (2)$$

where :

L_w = sound power (dB);

E_w = efficiency (dB);

P_{at} = atmospheric pressure (bar);

T = absolute temperature (°K);

D = pipe diameter (m);

U = flow speed (m/s).

Applying this formula to the exhaust gas in an exhaust system we observe that in different applications the "efficiency" parameter (E_w in the formula) is very important. This value can vary from a minimum of 75 to a maximum of 85 dB and must be detected experimentally. Since we have used for all the tests the same engine vehicle we can disregard this parameter and use for the calculation only the parts of the formula that are temperature dependent. So we can evaluate the expected ΔL_w with this simplified formula:

$$\Delta L_w(T) = (-17.5\log(T_1) + 45\log(U_1)) - (-17.5\log(T_2) + 45\log(U_2)) \quad (3)$$

where T_1 and U_1 are the temperature and the flow speed of the standard configuration (normal production) and T_2 and U_2 are the temperature and the flow speed using a heat exchanger.

With this formula we can plot the expected reduction of the jet noise (expressed in dB) versus the reduction of the gas temperature; the results are represented in [figure 2](#):

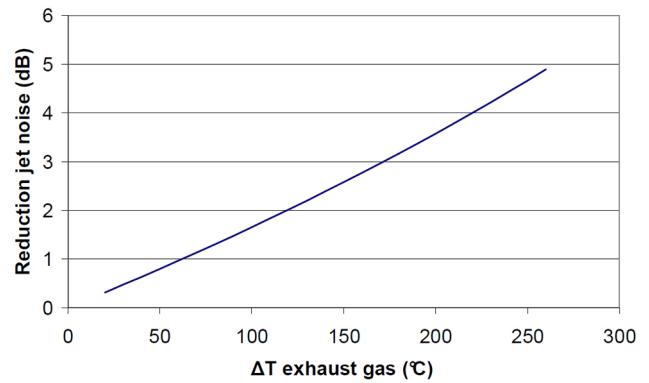


Figure 2. Expected reduction of jet noise at different exhaust gas ΔT reductions

So, for example, if we measure a temperature reduction of 150 °C, the expected reduction of the jet noise at high rpm is about 2.5dB.

The reduction of the exhaust temperature also influences the pipes resonance frequency according to the follow equation [9]

$$f = \frac{C_i}{2 * L} \quad (4)$$

where:

f = resonance frequency of the pipe;

C_i = sound speed at the specific temperature = $331.4 + 0.6 * T_i$;

L = pipe length.

Due to the fact that the sound speed C_i is dependent by the temperature.

In order to investigate the maximum effect of the gas cooling on the acoustic behaviour we designed a simple gas-liquid heat exchanger able to cool the exhaust gas with an efficiency of 50% ([figure 3](#)). The use of commercial heat exchangers was not suitable for our purposes, since beside high efficiency they also have a high pressure loss. In [figure 4](#) it is shown the pressure loss of the used gas-liquid heat exchanger compared with the central muffler of [figure 1](#) and with a commercial high efficiency automotive liquid-gas heat exchanger. It can be seen that the in-home designed heat exchanger has the same pressure loss of the central muffler: in this case the flow resistance is constant and the noise reduction is only due to the gas cooling (which is not possible to obtain with commercial high efficiency heat exchanger). Acoustic results obtained with this component are shown in the Results section.