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Short Communication

A note on the Strouhal number dependence of the relative importance of internal and external flow noise sources in IC engine exhaust systems

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Abstract

This note discusses issues related to the estimation of flow noise emission from rear mufflers in IC engine exhaust systems, through the analysis of measurements performed in a steady cold flow bench. First, the net acoustic power transmitted along the outlet pipe is obtained from in-duct pressure measurements. The in-duct power is then compared with noise measurements carried out in a semianechoic chamber, in order to distinguish between flow noise contributions associated with internal generation (muffler and tailpipe) and flow noise produced in the discharge process (interaction between the outgoing flow and the outside atmosphere). The ratio between the tailpipe in-duct acoustic power and the radiated acoustic power is analysed as a function of the Strouhal number. The results provide some information about the relative importance of internal and external sources.

1. Introduction

Flow noise is perhaps the most important problem in exhaust noise at high engine speeds. For this reason, the flow optimization of mufflers is an important part of their design if customer requirements and legislation limits are to be met [1].

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Flow noise in exhaust systems may be generated either at the exhaust exit, due to the interaction between the exhaust flow and the surrounding atmosphere, or at flow discontinuities and singularities inside the exhaust system [2]. The first mechanism is clearly unavoidable and therefore the only possibility for reducing it is to control the parameters governing the process. Regarding the second mechanism of flow noise generation, it is expected that sound produced by in-duct aerodynamic sound sources located close to the engine will not, in general, reach the exhaust exit, since it will be attenuated by the exhaust system itself. Hence, only the sources located at the rear muffler and the tailpipe need to be considered as flow noise sources relevant for exhaust noise emission.

Traditionally, flow noise characterization measurements are performed in free-field conditions [2]. However, such measurements do not provide sufficient information about the flow noise generated internally by the system (rear muffler and tailpipe), because they include both contributions, the flow noise generated internally and the flow noise generated during the discharge process.

In this work, in order to distinguish between both contributions, in-duct pressure measurements were first used to estimate the net acoustic intensity inside the tailpipe. Then, this estimate was compared with radiated noise measurements performed in semianechoic conditions. Any differences between the net transmitted power generated by the system and the measured exhaust noise should be attributed to the influence of the discharge process. In order to quantify this influence, the ratio of tailpipe and free-field acoustic powers was studied, revealing a clear dependence of this ratio on the Strouhal number. A simple mathematical expression is found for the power ratio. The results provide information on the role of the Strouhal number regarding the relative importance of internal and external sources, in the particular case considered.

2. In-duct acoustic intensity measurements

The system considered was a reverse expansion chamber with its corresponding inlet and outlet pipes, as represented in Fig. 1. The exhaust exit was located flush to the reflecting surface of the semianechoic chamber, so that shell noise associated with flow-excited vibrations was avoided. In

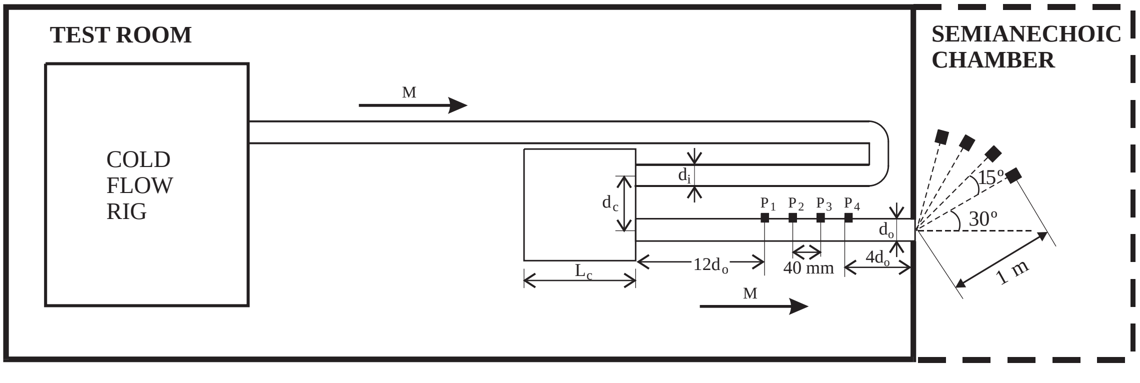

Fig. 1. Experimental settings.

the measurements carried out, the flow was provided by a cold flow bench where the air was supplied by a roots compressor. In-duct intensity was estimated from in-duct pressure measurements, through the determination of the forward and backward wave components p^+ and p^-, according to

$$I = \frac{1}{2\rho_0 a_0}\left[|p^+|^2(1+M)^2 - |p^-|^2(1-M)^2\right], \tag{1}$$

where ρ_0 and a_0 are the density and sound speed at the outside conditions, respectively, and M is the mean flow Mach number. These wave components were determined by means of a beamforming decomposition technique which allows for the use of more than two microphones, and whose main advantage when compared with conventional two-microphone techniques is its robustness in the presence of flow noise [3]. In the present study, four prepolarized Brüel & Kjær type 4935 microphones, mounted flush to the tailpipe duct wall, were used. The microphones were placed axially along the outlet pipe, taking into account the following issues: (1) the distance between the microphones was set to 40 mm, as a compromise between low-frequency errors [4,5] and high-frequency errors associated with the Nyquist criterion [6]; (2) since complex flow structures may be expected in the vicinity of the chamber outlet [2], the first microphone should be placed sufficiently far from the inlet of the outlet pipe, in order to ensure plane wave flow at this point [7]; by measuring the coherence function between microphones located in the same section but at different angles, it was found that 12 diameters was a convenient distance. Finally (3), the fourth microphone was located 4 diameters away from the exit of the outlet pipe in order to guarantee that the pressure measurements in the pipe were not affected by the discharge process.

The measurements were carried out for mass flow rates from 300 to 700 kg/h, at steps of 50 kg/h. The pressure-time histories of the microphones were recorded during 2 s with a PULSE acquisition system. This gives a good frequency resolution (with a sampling frequency of about 12 kHz) and a reliable signal. Simultaneously, the radiated acoustic pressure was measured by means of Brüel & Kjær type 4190 free-field microphones placed into the semianechoic chamber at 1 m from the exhaust exit, and at different angular positions with respect to the tailpipe axis (from 30° to 75° at steps of 15°), thus ensuring free-field conditions and allowing for the comparison between the exhaust noise measurements and the estimates of the net sound intensity generated internally by the system.

3. Experimental results and discussion

The net sound intensity transmitted along the tailpipe (I_t) was obtained as commented above, whereas the radiated sound intensity, I_r, was obtained in a similar way using the radiated acoustic pressure $p(r)$ measured in the semianechoic chamber and then computing the radiated sound intensity as $I_r(r) = p^2(r)/\rho_0 a_0$. This procedure should be sufficiently accurate for frequencies above the cut-off frequency of the seminaechoic chamber, which is of 100 Hz. For instance, the microphone error at 6 kHz is ±1 dB, and taking into account the errors in the measurement of pressure and temperature inside the semianechoic chamber, the resulting error in the intensity is ±0.14 dB.

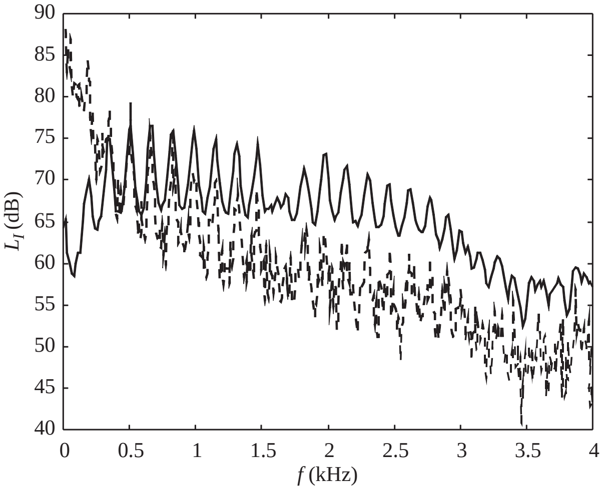

Fig. 2. Sound intensity spectra $\tilde{I}_r$ estimated from net intensity in outlet pipe (broken line) and measured radiated intensity I_r (solid line), for a steady flow with Mach number $M = 0.16$.

An example of the results obtained is shown in Fig. 2. In order to permit a proper analysis of the relative importance of the internal and external sources, the radiated intensity level L_{I_r} is compared with the intensity level $L_{\tilde{I}_r}$ that one would have if only the internal sources existed and one could assume that all the acoustic power in the tailpipe were radiated into the far field, this is, $\tilde{I}_r = (d_0^2/8r^2)I_t$, where d_0 is the tailpipe outlet diameter. In this way, if $\tilde{I}_r < I_r$ then the "excess" radiated intensity should be attributed to external sources (not considered in the definition of $\tilde{I}_r$), and if $\tilde{I}_r > I_r$ then the assumption which fails is that the tailpipe power is entirely radiated to the far field. In any case, both spectra show the presence of well-ordered spikes and troughs, which are related with the acoustics of the reverse chamber and the tailpipe, whereas in the absence of any chamber the radiated intensity spectrum would be essentially flat [2]. The presence of the chamber is also relevant for the scaling of overall values with flow velocity: while the intensity generated by the discharge of a free jet scales with a power of about 6, indicating the dominance of dipolar mechanisms at the discharge, when a chamber is present lower exponents are found in general, and the exponents themselves may depend on the chamber geometry [2].

According to these comments, in Fig. 2 different frequency ranges may be distinguished. At low frequencies, below 0.4 kHz, $\tilde{I}_r > I_r$, and thus in this frequency range not all the energy available is radiated acoustically from the open end of the pipe, but instead it may be absorbed due to interactions with the local flow field in the vicinity of the open end [8]. At high frequencies, above 1 kHz, one has $\tilde{I}_r < I_r$, and thus external sources associated with the jet discharge should be dominating the acoustic field; the contribution of such sources is expected to be particularly important in this frequency range [9].

In order to achieve a quantitative assessment of these features, and in view of the magnitudes measurable with the experimental set-up available, the ratio between I_r and $\tilde{I}_r$, denoted in the following by χ, was chosen for further analysis. This ratio is precisely the ratio between the radiated power to the in-duct power in the tailpipe:

$$\chi = \frac{I_r}{\tilde{I}_r} = \frac{2\pi r^2 I_r}{(\pi d_0^2/4) I_t} = \frac{W_r}{W_t}. \qquad (2)$$

A simple energetic analysis may help in the interpretation of this ratio. One may assume that the radiated acoustic power results from the addition of two terms: (i) the fraction of the tailpipe acoustic power that is actually radiated, that may be written as $\xi_r W_t$, where ξ_r represents the radiation efficiency; and (ii) the acoustic power W_j radiated by external sources associated with the jet discharge. Of course, these two terms cannot be evaluated separately, since the radiation efficiency depends on the details of the flow at the outlet, and conversely the flow structures responsible for the radiation by external sources are likely to be affected by the presence of the internal source [2]. From Eq. (2), one has

$$\chi = \frac{\xi_r W_t + W_j}{W_t} = \xi_r + \frac{W_j}{W_t}. \qquad (3)$$

Now, from Eq. (3), if $W_j \ll W_t$ then the power ratio χ will essentially represent the radiation efficiency ξ_r, whereas if $W_j > W_t$ then χ is essentially a measure of the relative magnitude of the internal and external sources. It is clear, from Fig. 2, that these issues depend strongly on the frequency range considered. Moreover, according to Kunz and Garcia [1,10] the ratio χ should depend on the Strouhal number, defined as: $St = fd_0/U$, where f is the frequency and U is the mean flow velocity. Therefore, a functional relationship between χ and the Strouhal number was sought.

With this purpose, 12 different reverse expansion chamber geometries were tested, ensuring a sufficiently wide variation range for the parameters governing the process. While the cross-section of the chamber was not changed, different values were considered for the rest of the geometrical dimensions (see Fig. 1): tailpipe diameters d_0 and inlet diameters d_i ranging from 30 to 51 mm; distances between inlet and outlet ducts of 73 and 146 mm; and chamber lengths ranging from 25 to 150 mm. As commented above, each of these 12 chambers was tested at nine different mass flow rates, the resulting outlet Mach numbers ranging from 0.1 to 0.34.

The values of log χ for all the measurements carried out are shown in Fig. 3 plotted against log St. In this figure, a clear change in the behaviour of χ can be observed around a Strouhal number equal to unity (log $St = 0$). In fact, for Strouhal numbers below unity, the behaviour of log χ is quite linear with log St, whereas for $St > 1$ a constant trend is observed. This change in the

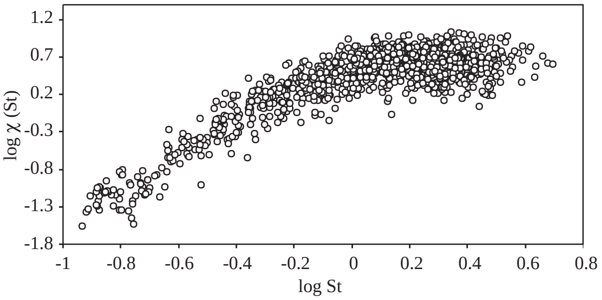

Fig. 3. Representation of the spectral behaviour of log χ against log St.

tendency might be related to the relationship between the acoustic wavelength of the emitted sound field and the characteristic size of the flow region affected by the jet discharge. This length is about $7d_0$ for a free jet, and somewhat smaller in the presence of discontinuities at the tailpipe inlet [2], as in the present case. The condition $St = 1$ is equivalent to $\lambda = d_0/M$, and with the Mach numbers considered this gives λ values between $3d_0$ and $10d_0$, which are consistent with the above-mentioned value. Accordingly, when $St<1$ it is likely that there will be some interaction between the acoustic field and the flow structures, so that some of the acoustic energy will be transferred to the mixing layer as kinetic energy. Conversely, when $St>1$ the acoustic wavelength is smaller than the flow region affected by the jet discharge, and these perturbations may thus be transported by the turbulent flow and be radiated. In this last case, χ ceases to be clearly Strouhal number dependent, which indicates that most of this dependence is related to the radiation efficiency ξ_r.

Following these ideas, a linear regression was performed for Strouhal numbers below unity, giving

$$\log \chi = (0.64 \pm 0.02) + (2.07 \pm 0.04) \log St, \tag{4}$$

with a correlation coefficient of 0.94 and a standard error of 0.19. This correlation should be valid for those geometries comprised in the geometrical limits indicated above. In Fig. 4 it can be observed that the regression line fits the measurements in a fair way. Since for Strouhal numbers above unity an average constant behaviour for χ was observed, it was assumed that χ does not depend on the Strouhal number for $St>1$. Thus, the final expression for χ as a function of St is

$$\chi(St) = \begin{cases} 4.37 St^{2.07} & \text{if } St \leqslant 1, \\ \chi(1) = 4.37 & \text{if } St > 1. \end{cases} \tag{5}$$

This $\chi(St)$ function shows an acceptable approximation to the measurement results, as can be checked in Fig. 5.

Once the $\chi(St)$ function was obtained, the radiated intensity was estimated from the tailpipe intensity making use of Eq. (2). The results of this estimate at three different Mach numbers are shown in Figs. 6–8. Good agreement is observed between the measured and the estimated radiated intensities at the spikes related with the internal source, mostly in the case of the highest flow velocity considered ($M = 0.2$). At the frequencies between these characteristic spikes, the

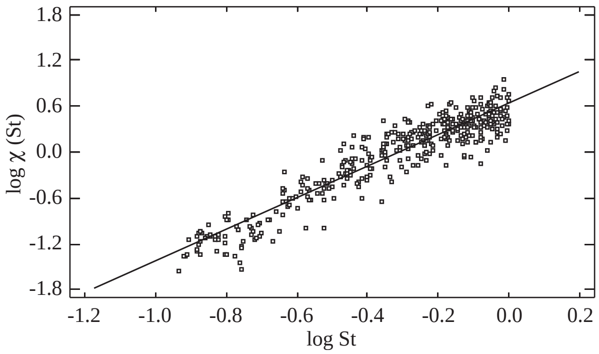

Fig. 4. log $\chi(St)$ representation for $St<1$: linear regression (solid line) and measurement values (squares).

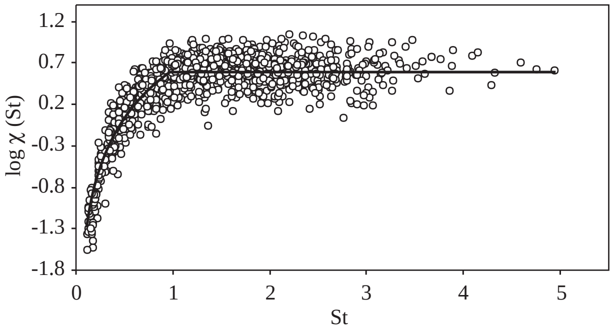

Fig. 5. Representation of the spectral behaviour of log $\chi(St)$: measured (points) and computed from Eq. (5) (solid line).

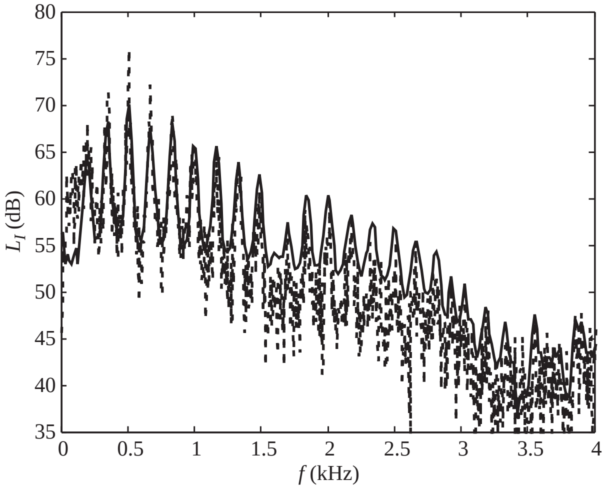

Fig. 6. Radiated sound intensity level $\tilde{I}_r$ estimated from tailpipe sound power level (broken line) and measured radiated sound intensity level I_r (solid line), for a steady flow with Mach number $M = 0.1$.

measured radiated power is higher, and this difference should be attributed to the external sources.

4. Conclusion

By means of the analysis of the ratio between acoustic powers inside the tailpipe and in free field, the relative importance of internal and external flow noise sources in exhaust systems has been studied. This power ratio has been obtained for a sufficiently wide set of a particular muffler geometry, but in any case its applicability should be restricted to the geometrical bounds considered. Similarly, while the results obtained might be qualitatively useful for other muffler geometries, previous work [2] suggests that the details can be strongly dependent on the particular scheme considered.

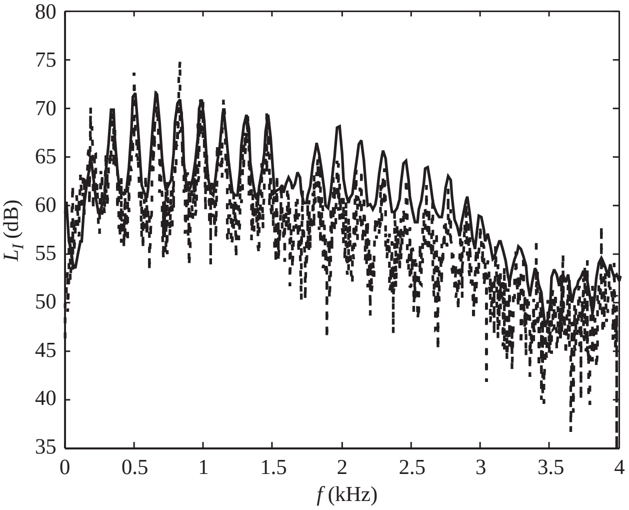

Fig. 7. Radiated sound intensity level $\tilde{I}_r$ estimated from tailpipe sound power level (broken line) and measured radiated sound intensity level I_r (solid line), for a steady flow with Mach number $M = 0.16$.

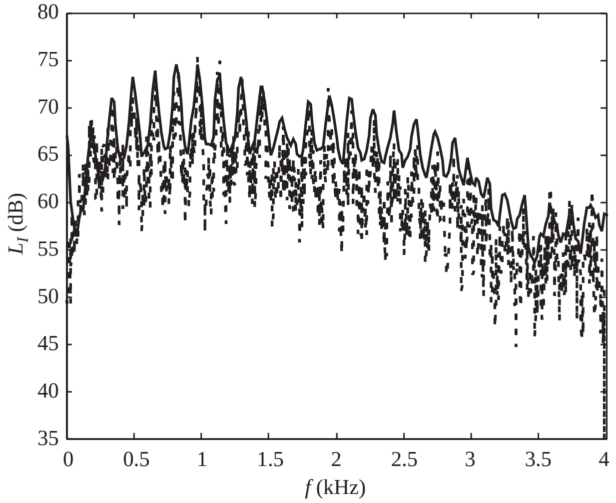

Fig. 8. Radiated sound intensity level $\tilde{I}_r$ estimated from tailpipe sound power level (broken line) and measured radiated sound intensity level I_r (solid line), for a steady flow with Mach number $M = 0.2$.

Accordingly with previous analyses found in the literature, the dependence of this factor on the Strouhal number has been established, and the results reveal that there is a clear change in tendency around $St = 1$, when the power ratio ceases to be governed by the Strouhal number; this may be qualitatively explained in terms of the interaction between the acoustic field associated with the internal sources and the flow field in the outside region affected by the jet discharge.

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