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IDENTIFICATION OF THE LINK BETWEEN DISTURBING ELEMENTS OF AUTOMOTIVE EXHAUST NOISE AND THE CONSTRUCTION OF THE EXHAUST SYSTEM

L. Dedene*, R. Valgaeren, M. Van Overmeire*, P. Guillaume***

* Dept. of Mechanical Engineering, Univ. of Brussels, Pleinlaan 2, B-1050, Brussels, Belgium

** Bosal Research NV, Dellestraat 20, B-3560, Lummen, Belgium

Tel.: +32-2-629.28.06 / Fax: +32-2-629.28.65 / Email: ldedene@vub.ac.be

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ABSTRACT
In this contribution a sound quality investigation concerning automotive exhaust noise will be presented. The investigation deals with the disturbing elements of exhaust noise (e.g. booming noise, hollow sound, whistle, ...). The investigation consists of three parts. The first part consists in determining a definition for each disturbing element (establish a sound quality catalogue). The next step is to establish a metric for each defined element. The final step is than to find the link between the established metrics and the geometry of the exhaust system. This is a difficult step due to the large number of components (tubes, baffles, perforations, ...). The exhaust noise is also influenced by the flow-induced noise. This paper will be focused on determining the link between the metrics and the exhaust system's geometry. For the disturbing element whistle the link between metric and geometry will be discussed in detail.

1 - INTRODUCTION

The sound quality of an exhaust system has become very important. Up to a few years ago, experts performed the sound quality assessment by listening. This is a subjective approach based on experience. To improve the design process there is a need for the objectivation of the sound quality. Once the sound quality can be determined objectively, one can set up demands and "measure" to what extend these are met, which allows a direct optimisation. Thus the sound quality is converted in a set of objective design parameters (metrics). The next step is then to find the link between the construction of the exhaust system and the metrics.

The sound quality of an exhaust system consists of two parts: the disturbing sound elements and the sound quality character. The disturbing sound elements are sounds that make the exhaust system sound deviant or strange. Generally, a disturbing element is only noticeable in a certain rpm range and/or in a specific engine operation. The sound quality character describes the sound perception of the exhaust system, such as sporty, cheap, ... First the disturbing elements have to be removed or at least reduced and afterwards the sound quality character can be evaluated. This article is focused on the disturbing elements.

The research discussed in this paper is performed on exterior tailpipe noise. The artificial head is positioned behind the car at 1.5 m from the tailpipe. This position combined with the use of insulating shields quasi eliminates all other noise sources and only exhaust noise is measured.

2 - APPROACH

The final goal of a sound quality research should be to determine the link between the sound perception and the construction of the product. Once this link is known each sound quality problem can be solved directly. This goal can be achieved in three steps: the sound quality assessment, analysis and identification. Each of these steps requires knowledge of a specific (and thus different) domain. The approach is schematically represented in figure 1. This approach is applicable to any product and for

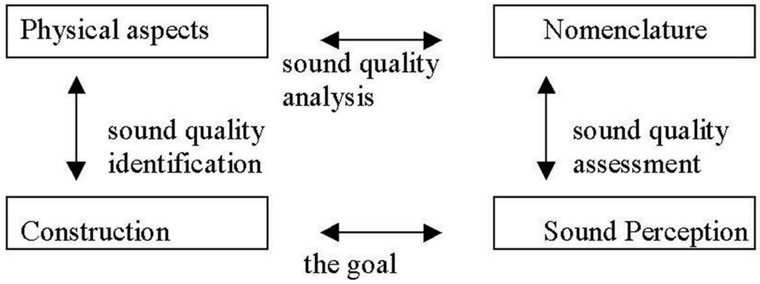

Figure 1: The used approach.

the disturbing elements as well as the sound quality character. The following explanation is based on the disturbing elements of exhaust noise.

The first step of the research is the sound quality assessment. This step consists in defining a "nomenclature". As many as possible disturbing sound elements should be identified by listening to the database of sound recordings. For each of these identified disturbing sound elements a name and definition should be determined. This step determines the relationship between sound perception and nomenclature.

The second step is the sound quality analysis. For each disturbing element the physical cause (e.g. a specific frequency component or time structure) must be determined. This step requires knowledge of signal analysis. Using extensive signal analysis and manipulation tools, such as tracked spectral analysis, order analysis, modulation spectra, psycho-acoustic metrics, real time filters, ..., the specific cause of each disturbing element should be determined. These specific properties can then be used to establish a metric for that disturbing element. This step determines the relationship between the nomenclature and the physical properties of the sound.

The last step is the sound quality identification. In this step, the link between the metrics and the construction of the exhaust system should be determined. This step requires knowledge and experience in exhaust system design and testing. For each disturbing element the necessary modifications to remove or reduce the disturbing element should be determined.

3 - SOUND CATALOGUE

The first step of the sound quality research is to define a nomenclature. This is a necessary step because the experts do not always agree upon the used nomenclature. Performing this step results in a sound quality catalogue.

To establish this sound catalogue a team of experts listened to the gathered sound recordings. They were asked to give a name and description about all the disturbing elements that occurred in the recordings. Using these results a definition was set up for each element. Such a definition consists of several aspects:

- Nomenclature in 4 languages (English/French/Dutch/German)
- Description of the element
- Engine operation in which the element occurs
- Engine type, some disturbing elements are specific to a certain engine type
- Possible causes

The final step of the sound quality assessment is to make a collection of at least 5 recordings for each disturbing element, this is necessary to perform the next step.

4 - METRICS

The disturbing elements of exhaust noise can be divided into two groups: the disturbing elements generated by specific frequency components of the exhaust noise and those generated by the time structure of the sound.

To establish a metric for disturbing elements that can be ascribed to frequency components, one can usually start from the frequency spectrum. The metric should gather the specific attributes from the calculated spectrum and monitor them in function of engine speed (or time).

For disturbing elements that can be ascribed to the time structure of the sound both the frequency spectrum and the signal envelope should be calculated. Using the signal envelope one can determine modulation frequencies, ... The specific characteristics of both should be combined to form the metric.

The metric describes the occurrence of the disturbing elements in function of engine speed or time. The magnitude is designed to be between 0 and 10, 0 means that the disturbing element is not audible and 10 means that the element occurs very heavily. An example of a metric is given in figure 2. The metric describes the occurrence of a boom during a wide open throttle run-up (a boom is a low frequent noise that may occur during a run-up or run-down). The boom occurs at a certain moment, lasts for a limited time and then disappears. The design of several metrics has been published in detail in earlier publications ([1,2]).

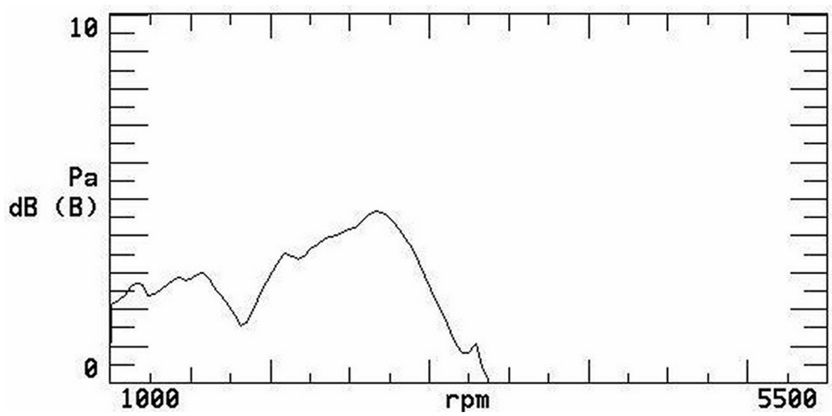

Figure 2: Metric for boom.

5 - WHISTLE

Determining the link between the metrics and the construction requires designing and testing of different exhaust systems. The cause of a disturbing element may be acoustical, vibro-acoustical or aero-acoustical. A problem that one sometimes runs into is a whistle. This whistle occurs during a certain rpm range and is subjectively very disturbing. A whistle can be ascribed to several causes:

- Whistle due to an acoustic coupling.
- Whistle due to a perforated area of a tube.
- Turbo-charger whistle, the frequency of the tone is proportional to the rotation frequency of the turbo-charger's rotor.

The case of the whistle due to a perforated area will now be discussed in detail. To investigate this, the set-up, shown in figure 3, was used.

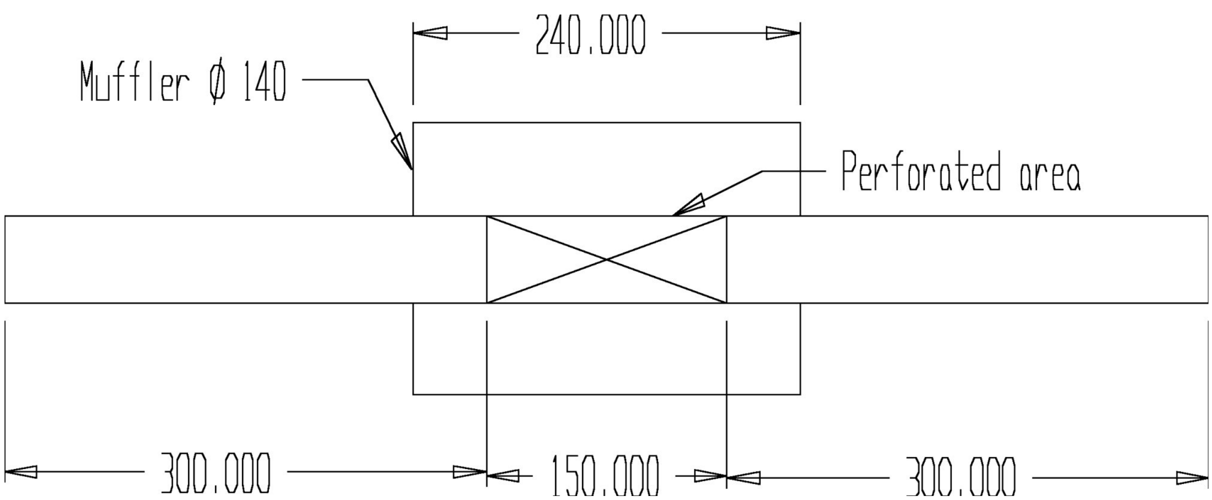

Figure 3: Exhaust system configuration.

The first observation we made was that the frequency of the tone depends on the flow rate. Since the flow rate is proportional to the Mach number, the Mach number can be used as variable. The plot of measured whistle frequency versus Mach number (figure 4) shows that there exists a reasonable linear relation between these two variables.

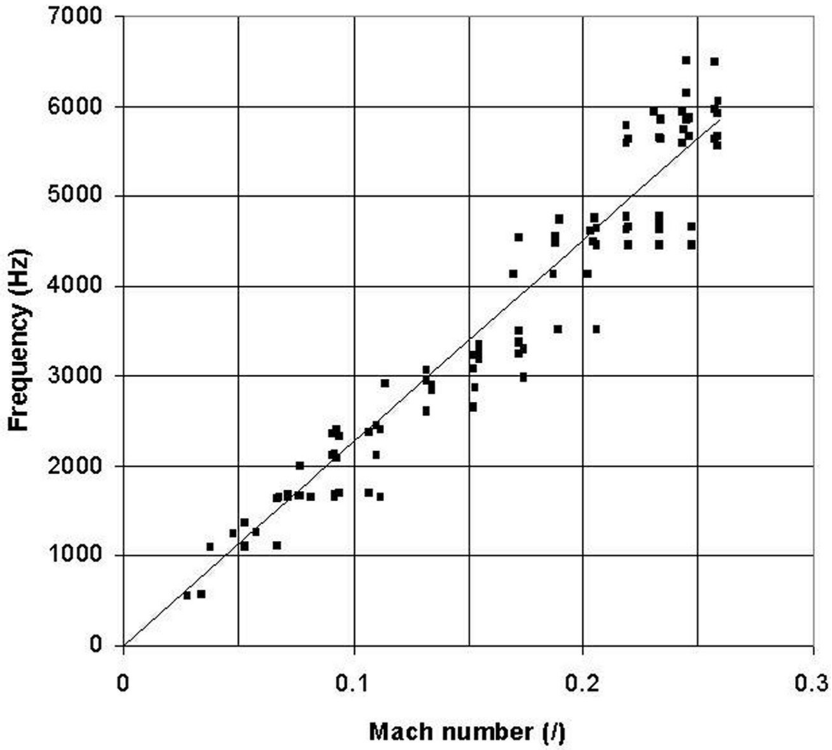

Figure 4: Whistle frequency versus Mach number.

To clarify the mechanism of whistle generation we can study the flow past one hole. The flow grazing over the hole will generate vortices. The flow will separate at the upstream edge of the hole, casting off a vortex sheet. The inflow and outflow (in the hole) will be maximum if the vortex spacing (λ) equals twice the diameter of the holes [3,4]. This demand can be transformed into Sr $\approx$0.5, Sr stands for the Strouhal number, defined as:

$$\mathrm{Sr} = \frac{\mathrm{f.L}}{\mathrm{U}}$$

with: f: frequency, L: characteristic dimension (diameter holes), U: vortex convection velocity.
This corresponds to the line found in figure 4. The vortex velocity is unknown and is (over) estimated by the main flow speed. The line in figure 4 corresponds to Sr = 0.44.
The above observations allow us to predict the whistle frequency if the flow rate (Mach number) is known, however figure 4 shows that specific frequencies are more likely to occur than other. This can be explained by figure 5.

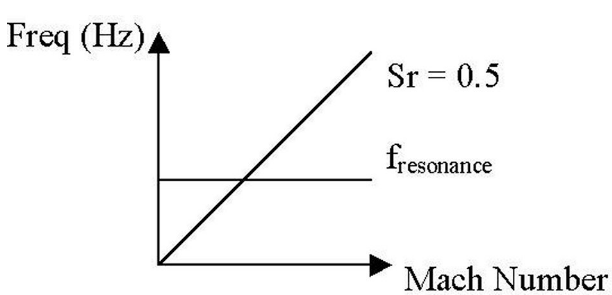

Figure 5: Mechanism whistle generation.

The demand Sr = 0.5 determines the whistle frequency that may occur at a specific Mach number. If a resonance exists at that frequency a whistle will occur. The resonance frequencies in this case are the cut-off modes of the tube.

The wave equation for a cylindrical duct is [5]:

$$p(x, r, \theta, t) = AJ_m(k_r r)\, e^{j(\omega t - m\theta - k_x x)}$$

with x: axial distance, r: radius, θ: angle, t: time, A: amplitude, J_m: Bessel function of order m.
The cut-off modes are solutions of this equation, for m higher than 0, for m = 0 one finds the plane wave solution. The first cut-off mode (m = 1) can propagate [5] for frequencies above (1,8412 is the abscis of the first maximum of the Bessel function of order 1):

$$f = \frac{1,8412c}{\pi d}$$

with c: speed of sound, d: internal diameter of tube.
The second cut-off mode (m = 2) can propagate for frequencies above (3,0542 is the abscis of the first maximum of the Bessel function of order 2):

$$f = \frac{3,0542c}{\pi d}$$

Figure 6 shows the frequency spectrum for two tube diameters and different Mach numbers. For the tube of Ø 42 mm the bump starts at about 5 200 Hz, this corresponds to the first cut-off mode of the tube. If a tube with a larger diameter (Ø 51 mm) is used the whistle occurs at a lower Mach number and the bump starts at a frequency that corresponds to the first cut-off mode for Ø 51, namely 4 300 Hz.

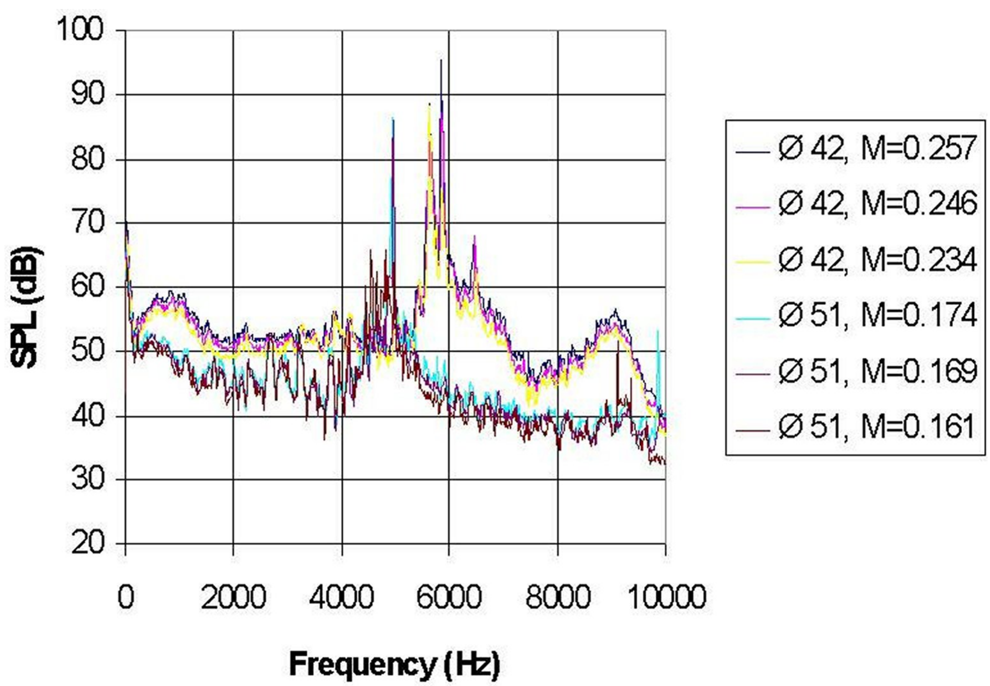

Figure 6: Frequency spectrum for different diameters and Mach numbers.

6 - CONCLUSION

The disturbing elements of exhaust noise have been investigated in this paper. The research consists of three steps:

- The different disturbing elements of exhaust noise are objectively defined (Sound catalogue + Audio-CD)
- The sound quality of an exhaust system concerning the disturbing elements can be measured objectively (metrics).
- The link between the established metrics and the construction of the exhaust system provides the knowledge to make the necessary modifications.

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