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Experimental methodology for turbocompressor in-duct noise evaluation based on beamforming wave decomposition

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ABSTRACT

An experimental methodology is proposed to assess the noise emission of centrifugal turbocompressors like those of automotive turbochargers. A step-by-step procedure is detailed, starting from the theoretical considerations of sound measurement in flow ducts and examining specific experimental setup guidelines and signal processing routines. Special care is taken regarding some limiting factors that adversely affect the measuring of sound intensity in ducts, namely calibration, sensor placement and frequency ranges and restrictions. In order to provide illustrative examples of the proposed techniques and results, the methodology has been applied to the acoustic evaluation of a small automotive turbocharger in a flow bench. Samples of raw pressure spectra, decomposed pressure waves, calibration results, accurate surge characterization and final compressor noise maps and estimated spectrograms are provided. The analysis of selected frequency bands successfully shows how different, known noise phenomena of particular interest such as mid-frequency "whoosh noise" and low-frequency surge onset are correlated with operating conditions of the turbocharger. Comparison against external inlet orifice intensity measurements shows good correlation and improvement with respect to alternative wave decomposition techniques.

1. Introduction

As competition from alternative-powered vehicles and environmental concerns increase, traditional internal combustion engines for automotive applications are facing tougher scrutiny by regulators and consumers.

Requirements for lower pollutant emissions (such as NO_x, CO, particulate matter, etc.) and higher efficiency (in order to reduce production of CO_2) are becoming more restrictive. An overview of these upcoming regulations is available from Op de Beeck et al. [1]. Consumers are also sensitive to the NVH (noise, vibration, harshness) performance of vehicles, and to the adverse impact of automotive emissions (including noise pollution), as shown by Brizon and Bauzer [2].

In order to match these expectations automotive engines are heavily downsized in terms of displacement and number of cylinders. However, these engines are still required to provide equivalent levels of torque and power output, so that turbocharger performance has to increase. Further discussion on downsizing, turbocharging and its importance to meet stricter emission policies is available in the work of Schumann et al. [3].

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However, it should be noted that this strategy is not without consequences. Stoffels and Schroeer [4] have shown how at certain operating conditions a downsized engine can radiate higher noise levels than its larger displacement equivalent.

An important contributor to engine noise radiation is the turbocharger compressor, as it operates at conditions close to its limiting surge line [5] due to increased turbocharging requirements.

However, increased noise *quantity* is not the only concern: it is also very relevant to take into account the *frequency* in which the noise increases, regarding attenuation possibilities as well as psychoacoustic perception of “sound quality” by the consumer, as shown in the above cited study [2] and in that of González et al. [6].

In this paper, a methodology is proposed to evaluate the noise emission of the compressor through its inlet and outlet pipes in selected zones of the compressor map of operating conditions. It allows a simple and clear visualization of noise phenomena and their frequency distributions at all possible operation points of the turbocharger system.

Although compressor manufacturers sometimes provide these noise maps [7], they usually refrain from providing an adequately referenced and step-by-step methodology to reproduce them.

Reviewing the existing literature on turbocompressor noise a variety of very different measurement techniques can be found, from the two-sensor, in-duct approach of Tiikoja et al. [8] to simple single-sensor pressure levels and external commercial noise-meters [9].

However, these works focus on the research of different phenomena (transmission loss [8], effect of flow incidence angle [9], sound generation by rotating stall [10], source characterization [11], etc.), not on the acoustical methodology itself nor on the particular setup considerations and restrictions that each measurement technique imposes.

This work wishes to address the shortcomings of the existing literature by proposing an experimental methodology and discussing the details of its theoretical background, its implementation, its range of application, and the processing required to produce standardized results.

In order to provide some illustrative results, the methodology proposed in this paper has been applied to a series of experimental tests in a flow bench where a small automotive turbocharging group has been installed. Applicability of the methodology and comparison with other methods is also discussed.

2. Theoretical methodology

2.1. Sound intensity in flow ducts

While it is possible [9] to rely on a single sensor to measure the scalar *sound pressure level* (SPL) of the flow at a certain location of a duct, more sophisticated approaches are needed to estimate the *sound intensity level* (SIL) that is propagating through the duct.

It is important to consider that the scalar magnitude of sound pressure level at a point can be influenced by the precise geometry of that section and by nodes and reflections that may occur in the duct, whereas sound intensity is a vectorial magnitude that remains almost constant along the duct (except for small dissipation losses), and thus is a more robust indicator of noise emission.

The basis of the intensity measurement methods is to consider that the pressure signal $x(t)$ measured at a given point of a duct is the linear superposition of a pressure wave x^+ travelling downstream and another pressure wave x^- travelling upstream (sometimes referred to as forward and backward waves, respectively [12]) so that:

$$x(t) = x^+(t) + x^-(t) \tag{1}$$

By comparing the pressure information at two or more spatial positions it is possible to infer how the waves are propagating along the duct in each direction; this information is not available by means of a single sensor.

When using this wave decomposition approach, the sound intensity is commonly estimated following the definition proposed by Morfey [13] and successfully derived by Dokumaci [14] from physical principles [15–17]:

$$I = \frac{1}{\rho a}\left(|\mathbf{X}^+|^2(1+M)^2 - |\mathbf{X}^-|^2(1-M)^2\right) \tag{2}$$

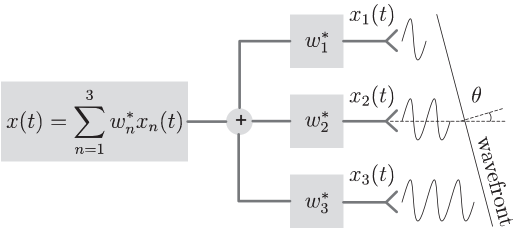

Fig. 1. Diagram of a narrowband beamformer with three elements tuned to a Direction of Arrival (DOA) of θ.