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Numerical and experimental analysis of automotive turbocharger compressor aeroacoustics at different operating conditions

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ABSTRACT

Centrifugal compressor aeroacoustics are analyzed by means of a three-dimensional CFD model. Three operating points at nominal compressor speed are simulated ranging from best efficiency point to near-surge conditions. Experimental measurements are obtained using a steady flow rig mounted on an anechoic chamber. URANS and DES predictions of compressor global variables and pressure spectra are compared against experimental measurements. Flow-induced noise increases as the operating point moves toward surge line. Stall at the suction side of the blades exists even for high mass flow conditions, causing a high frequency boundary layer oscillation. Low momentum cells rotating at the diffuser are found at points closer to surge, causing the so-called *whoosh noise*. Inducer rotating stall is also present at these conditions. Point closest to surge shows a rotating tornado-type vortex at the inducer, determining a moving low pressure region that increases low frequency noise content.

1. Introduction and literature review

Literature survey about the ISO 362 vehicle pass-by noise test conducted by Braun et al. (2013) indicated that intake and exhaust systems are regarded as one of the main noise sources by most of researchers.

Particularly, Stoffels and Schroeer (2003) showed that radiated noise in low speed range (below 2800 rpm) of a downsized turbocharged gasoline powertrain is higher than that of an engine with the same power but larger displacement. It is a common belief that development of strongly down-sized engines with increased low speed torque has increased turbocharger compressor airborne noise (Evans and Ward, 2005), due to the operating points being closer to surge region (Teng and Homco, 2009).

Compressor flow-induced acoustics is becoming a major issue for automotive car makers. It is therefore understandable the increasing number of publications concerning this topic in the last decade, most of which are mainly experimental. Works by Evans and Ward (2005); Teng and Homco (2009) or Sevginer et al. (2007) identified compressor NVH issues by measuring noise radiation. Particularly, a broadband noise denoted as *whoosh noise* was identified. A common way to reduce noise radiation was the use of resonators in compressor outlet hose.

Nevertheless, if flow phenomena leading to whoosh noise were known, quieter centrifugal compressors could be designed. Most common way of getting some insight of compressor aeroacoustics has been the use of wall flush mounted pressure transducers.

Ha et al. (2013) measured the internal pressure fluctuation of a centrifugal compressor at different operating conditions at three stages: before the leading edge, after the trailing edge and after the diffuser. Moreover, external microphones were also used. SPL at impeller inlet presented a sudden increase when moving from best efficiency point (BEP) to stall conditions, due to onset of flow detachments and backflows. Impeller and diffuser outlet spectra are alike: they show a broadband increase in 2–4 kHz frequency range when reducing mass flow from BEP. At stall conditions, a tone appears at 90% of rotation order, being attributed to rotating stall. Orifice noise measured with external microphones is consistent with compressor inner probes spectra: amplitude in low frequency range is increased as mass flow is reduced.

Other experimental studies such as the ones carried out by Mongeau et al. (1995) or Raitor and Neise (2008) are also based on a detailed instrumentation with pressure transducers. This approach is quite challenging for passenger car turbocharger compressors due to their small size. In the last years, though,

Abbreviations: BEP, best efficiency point; BPF, blade passing frequency; CAD, computer-aided design; CBV, compressor by-pass valve; CFD, computational fluid dynamics; DDES, delayed DES; DES, detached eddy simulation; IDDES, improved DDES; LES, large eddy simulation; MoC, Method of Characteristics; NIST, National Institute of Standards and Technology (US); NPL, National Physical Laboratory (UK); NVH, noise, vibration, and harshness; PS, (blade) pressure side; PSD, power spectral density; RANS, Reynolds-averaged Navier–Stokes; SPL, sound pressure level; SS, (blade) suction side; VT, volute tongue; WMLES, wall-modeled LES.

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researchers are able to investigate centrifugal turbomachinery aeroacoustics using CFD because of the increase of computational capabilities.

Liśkiewicz et al. (2014) performed an experimental investigation of centrifugal blower acoustic signature in which pressure spectral maps were obtained at different probe locations for different operating conditions. Subsynchronous narrow band disturbances were found even at stable points. Before onset of surge-related noise, the acoustic signature notably changes at the maximum compression ratio point. This change was attributed to inlet recirculation.

Jyothishkumar et al. (2013) analyzed the unsteady flow of a ported shroud centrifugal compressor at design and near-surge conditions using LES. Frequency decomposition of tangential velocity traces obtained at several diffuser probes was performed. A tone at 50% of rotational speed was observed at the operating point with less mass flow rate, indicating the existence of rotating stall at near-surge conditions.

Bousquet et al. (2014) conducted a numerical study of a centrifugal compressor. Three operating points were studied from peak efficiency to near stall conditions. A virtual probe linked to the relative frame located at 90% span at the impeller inlet was used for pressure spectral analysis. Stator vane passing frequency tone is the main feature for the two operating conditions with higher mass flow. Near stall, lower frequency content appears, particularly a tone at a frequency 6 times the rotation order. Frequency content below rotation order was not investigated.

Mendonça et al. (2012) investigated turbocharger compressor aeroacoustics by means of CFD. SPL spectra revealed a narrow band noise at a frequency about 70% of rotational speed. Leading-edge detachment and stalled passages were found. Rotating stall was detected in the form of a low momentum region that rotates at a slower speed than the impeller, being regarded as the source of the narrow band noise. The authors considered that tip leakage pushed the low momentum region to the adjacent passage thus allowing the stalled passages to recover.

Fontanesi et al. (2014) performed detached eddy simulations of a turbocharger compressor with a compressor by-pass valve (CBV). Two operating points at the same isospeed were investigated: one close to surge and the other at a two times higher mass flow rate. At low frequency range (below 5 kHz), simulation with higher mass flow provides a lower overall noise than the point close to surge. A narrow band noise at 2500 Hz stands out in both spectra, which is attributed to periodic flow detachment and re-attachment at the CBV junction. Experimental measurements also detect the aforementioned narrow band.

The literature review proves that CFD is useful to investigate turbocharger compressor flow-induced acoustics, because it could be used to find an explanation for pressure spectra features, such as whoosh noise. In this paper, simulations of three centrifugal compressor operating points at same speed are studied, comparing URANS and DES turbulence models against experimental measurements.

The paper is organized as follows. Section 2 describes the CFD model used in this paper. Comparison of URANS and DES global variables and acoustic spectra against experiments is performed in Section 3. Section 4 is devoted to the investigation of the flow field in order to identify the phenomena responsible for the acoustic signature features. Finally, paper conclusions are provided in Section 5.

2. Numerical model

A CFD model of a turbocharger compressor was developed using STAR-CCM+ (2013). The impeller with 6 full and 6 splitter blades was digitalized along with the vaneless diffuser and compressor volute. The domain depicted in Fig. 1 is completed with the

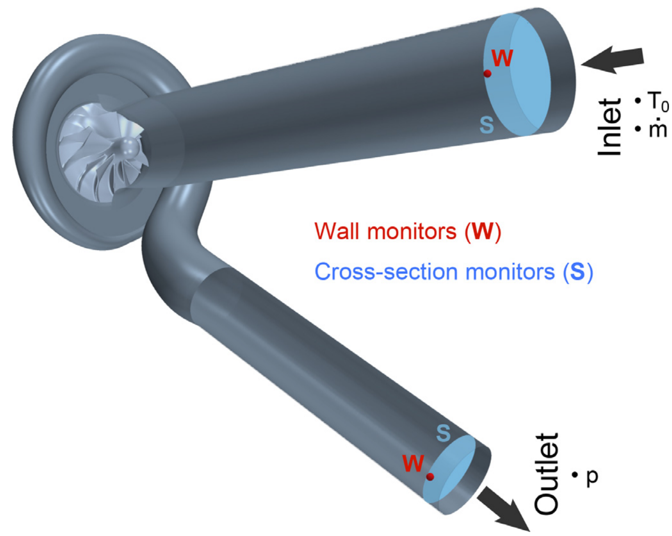

Fig. 1. CFD domain including monitor types and locations and flow variables imposed at the boundary conditions.

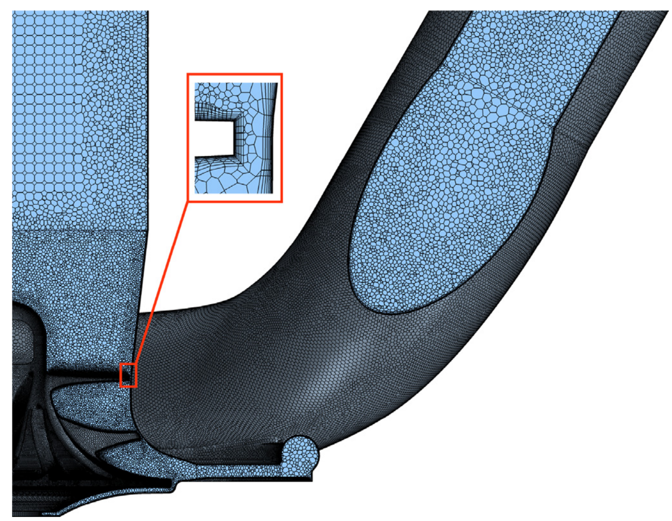

Fig. 2. Slice of computational grid, showing a close-up of tip clearance and the boundary layer mesh inflation. Inlet and outlet ducts present the displayed grid pattern until their respective boundary.

extrusion of five-diameters-long inlet and outlet ducts. The overall mesh consists of 9.5 million polyhedral cells. Backplate clearance along with tip gap are considered in the model, as can be seen in Fig. 2. CAD clearance is considered instead of actual tip gap existing when compressor is running because Galindo et al. (2015) found that centrifugal compressor noise production in near surge conditions is not sensitive to tip clearance ratio.

Transient simulations with a segregated, second-order time accurate solver were performed with a time-step size so that the impeller mesh turns 1° per time step, which was selected in accordance with the sensitivity analysis conducted by Navarro (2014). Impeller rotation was considered using the rigid body motion approach.

Fixed outlet pressure and inlet mass flow rate boundary conditions were used, as indicated in Fig. 1. Broatch et al. (2014) proved that NRBCs are not mandatory to predict the compressor acoustic signature provided that a pressure decomposition algorithm is used (further information is provided in Section 3.3). Three operating conditions at 1.4, 1.8 and 2.5 times surge mass flow at a constant compressor speed close to 160 krpm were simulated. According to Serrano et al. (2013), compressor heat transfer with

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