

Effect of Aerodynamically Induced Pre-Swirl on Centrifugal Compressor Acoustics and Performance

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ABSTRACT

The effect of aerodynamically induced pre-swirl on the acoustic and performance characteristics of an automotive centrifugal compressor is studied experimentally on a steady-flow turbocharger facility. Accompanying flow separation, broadband noise is generated as the flow rate of the compressor is reduced and the incidence angle of the flow relative to the leading edge of the inducer blades increases. By incorporating an air jet upstream of the inducer, a tangential (swirl) component of velocity is added to the incoming flow, which improves the incidence angle particularly at low to mid-flow rates. Experimental data for a configuration with a swirl jet is then compared to a baseline with no swirl. The induced jet is shown to improve the surge line over the baseline configuration at all rotational speeds examined, while restricting the maximum flow rate. At high flow rates, the swirl jet increases the compressor inlet noise levels over a wide frequency range. At low to mid-flow rates, on the other hand, the swirl jet reduces the broadband whoosh noise in the 4-11 kHz range. Mild surge detected for the baseline configuration in the 15-35 Hz range at mid flow rates and high speeds is also suppressed with the swirl jet configuration due to favorable local changes in slope of the compressor characteristics.

CITATION: Figurella, N., Dehner, R., Selamet, A., Miazgowicz, K. et al., "Effect of Aerodynamically Induced Pre-Swirl on Centrifugal Compressor Acoustics and Performance," *SAE Int. J. Passeng. Cars - Mech. Syst.* 8(3):2015, doi:10.4271/2015-01-2307.

1. INTRODUCTION

Centrifugal compressors used in automotive turbochargers often operate near the stability limit or in close proximity to the surge line. In order to improve the range of stable operation, swirl generating devices can be added upstream of the compressor impeller, to reduce the incidence angle between the incoming air flow and the leading edge of the impeller blades, thereby reducing flow separation on the suction surface of the blades. While inlet guide vanes (IGVs) including axial IGVs [1,2,3] and variable radial IGVs [4] have been shown to improve surge margin [1], swirl inducing air injections [5] are an alternative method, where a bypass is installed to recirculate compressed air downstream of the compressor through air jets upstream of the impeller. Possible benefits of swirl inducing air injections include the absence of vanes, which physically obstruct the flow leading to pressure losses, and less complexity, since no vane actuation is required (a simple valve could be used instead to control swirl). In addition, the recirculated air increases compressor mass flow rate relative to that of the engine and therefore improves surge margin for a given engine operating point.

With the expanding implementation of turbochargers into passenger car applications, compressor acoustics is also receiving greater attention. Broadband flow noise, also referred to as "whoosh" or "blow noise," has been observed over a range of 1.5-3.5 kHz [6, 7, 8] (for compression-ignition engines) or 5-7 kHz [9] and 4-12 kHz [10] (for spark-ignition engines) while operating in the vicinity of the surge line or near the peak compressor pressure ratio for a given operating speed. Therefore, the objective of the present study is to determine the effect of aerodynamically induced pre-swirl on both compressor performance and acoustics.

Following this introduction, Sec. 2 briefly describes the experimental setup, including the facility, instrumentation, and turbocharger. Section 3 discusses the time-averaged compressor performance data. Section 4 presents the acoustic measurements as total sound pressure level in the frequency domain, followed by concluding remarks in Sec. 5.

2. EXPERIMENTAL FACILITY

The present work provides detailed compressor performance and acoustic measurements from a turbocharger installed on the turbocharger test bench at The Ohio State University [11], shown in Fig. 1. This bench is located in a semi-anechoic room, which is isolated from external sound sources, including the screw compressor and oil pump. The facility has “warm flow” capability by delivering up to 15 kW of electric heat to the flow upstream of the turbine inlet, while the compressor flow circuit is decoupled from the turbine side to maximize flexibility.

Time-averaged compressor performance data is obtained from absolute piezoresistive pressure transducers and thermocouples installed in the compressor inlet and exit ducts along with mass flow rate from a calibrated orifice flow meter and rotational speed from an inductive sensor. Flush-mounted transducers measure upstream pressure 94 mm from the inducer plane of the impeller and downstream pressure 49 mm from the volute exit.

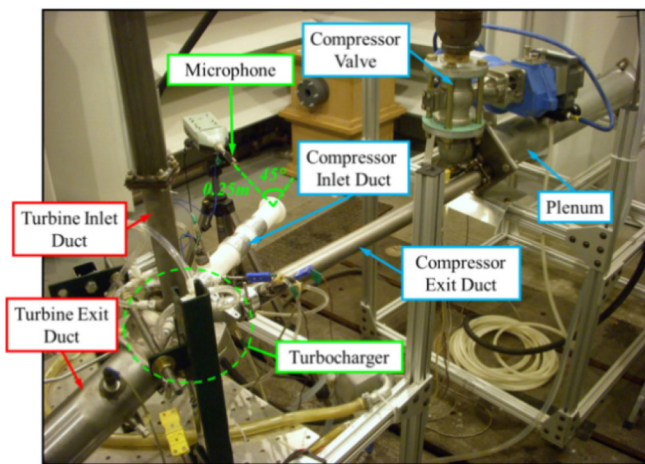


Figure 1. Turbocharger test bench.

Time-resolved pressure fluctuations are measured by a dynamic piezoelectric transducer, which is flush-mounted with the internal wall of the compressor inlet duct at the same axial location as the absolute pressure transducer. The sound propagating externally from the compressor inlet duct is measured with a 1/4" microphone which is positioned 0.25 m from the bellmouth of the inlet duct, at an angle of 45° from the duct axis (recall Fig. 1).

The turbocharger studied is from the right-bank of a 3.5L V6 turbocharged engine. The compressor has a 51 mm exducer tip diameter and a trim of 72, where $Trim = (Inducer\ Diam. / Exducer\ Diam.) \times 100$. The compression system employed in the study incorporates a well-defined plenum, which is connected to the compressor exit duct and an additional duct containing a control valve. This system was studied at 1/8 (1.155 L) of the full plenum volume. In addition to the plenum, compressed air occupies the volume between the diffuser inlet of the compressor and the plenum inlet along with that between the plenum exit and the control valve, with a total compressed volume of 2.7 L.

In this study, a “swirl jet” configuration is explored, where an air jet is used to aerodynamically induce swirl within the compressor inlet duct, in order to reduce inducer incidence. The layout of this configuration is shown in Fig. 2 where an additional flow path or “bypass” (shown in red) was added which allowed compressed air from the plenum to recirculate back to the compressor inlet duct.

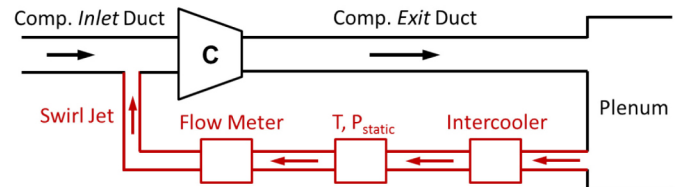


Figure 2. Compressor bypass (shown in red) for swirl jet configuration.

The orientation of jet introduction into the compressor inlet duct and sizing of the jet throat are critical design features of the bypass which were optimized utilizing compressor CFD predictions. An oversized jet throat would bleed an excessive amount of air, such that compressor pressure ratio is significantly reduced (for fixed turbine power). This scenario would degrade low-speed, high-load engine performance, where the wastegate is already closed to extract maximum turbine power to drive the compressor. On the other hand, the jet throat size must be sufficiently large in order to generate sufficient swirl and bypass flow so that improvements in sound quality and surge margin may be realized. Three-dimensional CFD predictions were utilized to appropriately size the throat diameter of the swirl jet converging nozzle at 3 mm, which is introduced into the compressor inlet duct with a nominal inner diameter of 39 mm, as shown in Fig. 3. The jet was oriented perpendicular to the axis of rotation and tangent to the internal wall of the compressor inlet duct at the introduction point in order to maximize the tangential velocity near the inducer blade tips.

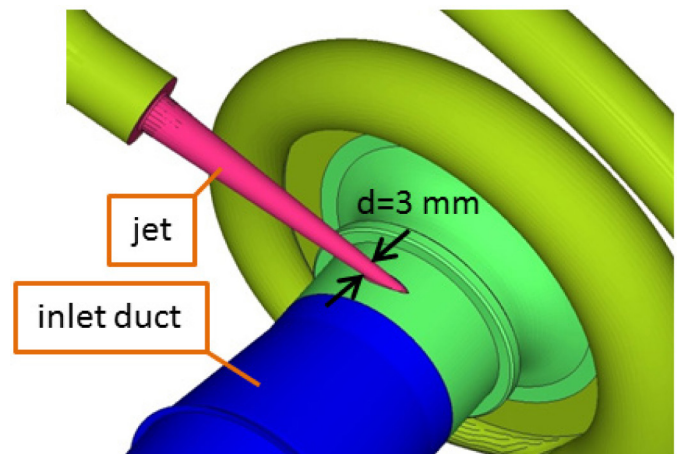


Figure 3. Jet orientation.

The jet induces swirl in the same direction as impeller rotation, such that it decreases the incidence angle of incoming air flow relative to the leading edges of impeller blades, as shown in Fig. 4. This configuration reduces the tendency for the flow to separate from the suction surface of the blades at low flow rates, specifically near the blade tips where the incidence angle is most sensitive due to the higher angular velocity of the blade.

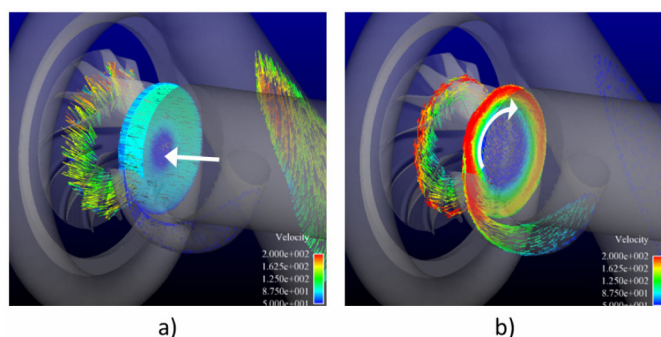


Figure 4. Compressor inlet flow-field, a) without swirl jet, and b) with swirl jet.

In addition, CFD was utilized to optimize the axial distance between the jet and the inducer plane, as shown in Fig. 5, where the final selected position balances tangential velocity uniformity around the periphery with rotational momentum dissipation.

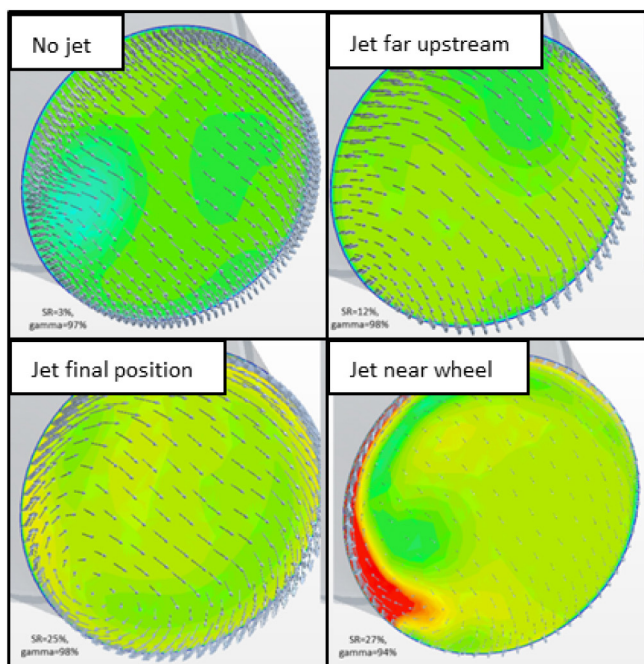


Figure 5. Compressor inlet flow-field with relative axial distances from jet to inducer.

The CFD optimized geometry was utilized to construct a rapid prototype part for testing, as shown in Fig. 6.

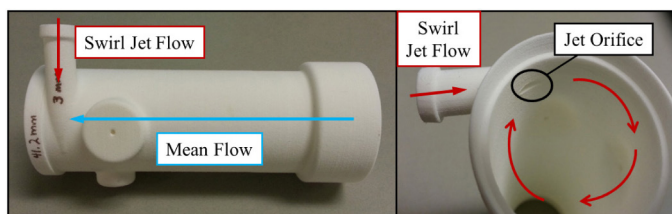


Figure 6. Swirl jet duct section.

The swirl jet is located just downstream from the instrumented portion of the compressor inlet duct, at an axial distance of 71 mm from the inducer. The full compressor inlet duct with instrumentation and swirl jet are shown in Fig. 7.

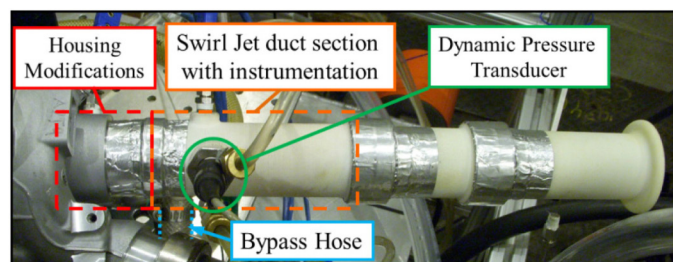


Figure 7. Compressor inlet duct layout for swirl jet configuration.

For the swirl jet configuration, compressed air is bled off through the bypass, and therefore the downstream compressor orifice flowmeter no longer measures the entire flow passing through the compressor. In order to measure the mass flow rate through the bypass, instrumentation was installed within it, including an Omega FLMG Series flowmeter (recall Fig. 2) and a type T thermocouple along with a Validyne static pressure transducer. A small air to water intercooler was located upstream of all instrumentation in the bypass to slightly cool the flow in order to avoid exceeding the temperature limit of the bypass flowmeter. The compressor bypass was constructed of high pressure and temperature 1/2" reinforced PVC tubing, with a total length of approximately 1.73 m. No valves were installed within the bypass for this setup, allowing the downstream pressure and jet orifice size to dictate the flow rate through the bypass.

The swirl jet configuration was tested with an "inlet step" compressor cover installed as shown in Fig. 8b, where a 3 mm step (reduction in cross-sectional area) exists in the compressor inlet just upstream of the inducer blade tips. This inlet step configuration was selected for use with the swirl jet based on CFD predictions [12], which revealed the most substantial reduction in whoosh noise when it is used in combination with (IGV) swirl. Here the swirl jet configuration is compared with a "baseline" configuration where the jet feature and bypass were not present and no swirl was induced. For the baseline configuration, an "unmodified" compressor cover was installed as shown in Fig. 8a, with a 3 mm deep by 3 mm wide groove around the circumference of the compressor inlet, just upstream of the inducer blade tips.

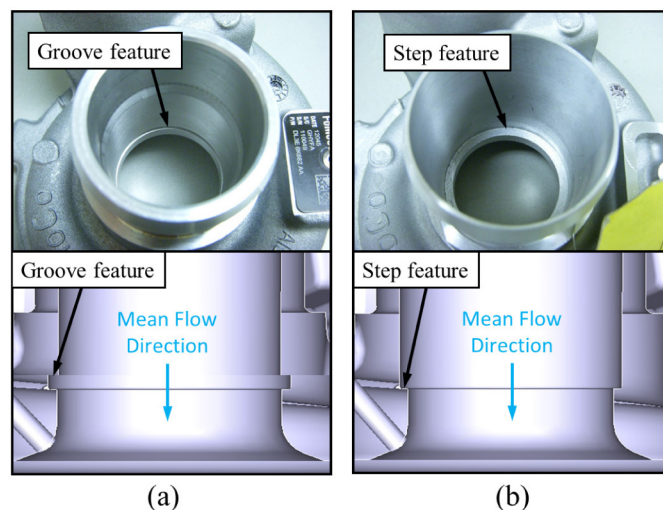


Figure 8. Compressor housings: (a) baseline with 3 mm x 3 mm groove (b) 3 mm "inlet step" modification.