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# Effect of bleed slots on turbocharger centrifugal compressor stability

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ABSTRACT

Bleed slots located in the inducer region of centrifugal compressors have been demonstrated to extend the surge margin with minimal negative impact on performance. This paper describes the impact of bleed slots on surge margin enhancement in a turbocharger centrifugal compressor used for heavy duty diesel engines. The study included evaluation of pressure instabilities throughout the compressor map, characterization of dynamic phenomena occurring at low mass flow rates (mfr), and elucidation of the impacts of bleed slots on the compressor stability and surge line.

A comparison of the compressor performance was performed between open and blocked bleed slots. Pressure instability levels were measured throughout the accessible compressor map using a high frequency response pressure transducer at the compressor outlet for the two cases. Static and dynamic pressure measurements were acquired within the diffuser using pressure taps and high frequency response pressure transducers.

The compressor with open bleed slot showed lower instability levels at low mfr when not experiencing deep surge. Spectral analysis at low mfr showed that the bleed slot suppresses broadband frequencies linked to piping resonance and below the rpm frequency, thus improving the overall stability. When excited, these frequencies create periodic flow disturbances that originate from the low pressure region below the tongue, at low mfr. The low pressure perturbations are then convected by the flow and propagate around part of or the entire perimeter, depending on the compressor speed.

## 1. Introduction

Regulations regarding the reduction of greenhouse gas emissions and fuel consumption of internal combustion engine require improving its efficiency. One way to achieve that is to increase the intake engine air density thereby also improving the energy to weight ratio. Hence, the use of turbochargers is a very common technical solution for forced induction of internal combustion engines, especially in the case of diesel engines. The selection of the best turbocharger for a specific application is key to obtain optimum operation. Design requirements for the turbocharger compressor is to cover the largest range of operation. Thus, it should efficiently produce sufficiently high pressure ratios at low mass flow rate (mfr) and to be large enough to handle the maximum engine air flow rate. It becomes then crucial to identify and study the limiting phenomena occurring at both high and low mfr.

At relatively high mfr, compressor performance is limited by choking. Since compressors increase the pressure, they develop adverse pressure gradients. As in many other fluid mechanics systems, adverse pressure gradients in compressors can lead to instabilities with localized regions of recirculation and eventual stall. This can occur at any point on the compressor performance map but is more common at low or very high mfr. At low mfr, the range of operation of turbo-compressors is restricted by the occurrence of instabilities, either static such as in stationary stall, or dynamic such as rotating stall and surge. Stationary stall can be caused by high incidence (e.g. at off design operating conditions) or rapid flow turning (e.g. on the shroud side for centrifugal compressors or in returning channels or piping (Sorokes, 1998)) and is responsible for the increase in instability levels, vibrations, and performance losses of the compressor. Furthermore, centrifugal compressors may operate with axisymmetric stall developing on the impeller blade tip or with stationary non-axisymmetric stall produced by the volute design and by the tongue (Fink et al., 1992). Nevertheless, this is generally acceptable because most of the pressure rise is produced by centrifugal effects, which are present even with separated flow.

Rotating stall and surge have been widely studied e.g. Fink et al. (1992) and Hansen et al. (1981). Greitzer (1976) distinguished between rotating stall from surge in axial compressors. Rotating stall can be considered as steady in the meridional direction and non-axisymmetric whereas surge is defined as an unsteady

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axisymmetric phenomenon related to the entire compressor system (including the connecting pipes). The Moore–Greitzer model developed for axial compressors (Moore and Greitzer, 1986), and eventually demonstrated for centrifugal compressors (Hansen et al., 1981) and in particular for small turbocharger centrifugal compressors (Galindo et al., 2007), is a one-dimensional model which is the base for most of the models used to predict the behavior of compressors during surge. In addition to instabilities in the impeller and diffuser, for centrifugal compressor with a volute (intended to direct the flow after the diffuser), this element can induce instabilities that can reduce the operating range (Guo et al., 2007). More recently, computational fluid dynamics has allowed prediction of the flow patterns in all parts of the compressor (Semlitsch and Mihaescu, 2016).

Surge can be either mild or deep and is characterized by localized region of reverse flow and by increase in vibrations and pulsating pressure. In the case of deep surge, complete flow reversal occurs during part of the surge cycle. Being a system phenomenon, surge does not only depend on the compressor itself but also on all the surrounding elements and can differ depending on the piping and occurrence of engine-like pulsating flow (Galindo et al., 2009). Unlike mild surge that occurs at the natural frequency of the compression system, deep surge occurs at lower frequencies (Jungowski et al., 1996) set by the outlet plenum emptying and refilling times (Fink et al., 1992). In the case of mild surge, the annulus average mass flow oscillates but remains positive whereas in the case of deep surge, the oscillations are large and usually negative during part of the cycle. While mild surge can usually be tolerated because of its relatively low level oscillations, deep surge can be very harmful and eventually may lead to the failure of the system.

Commonly, the surge line on an operating map represents the onset of deep surge or the acceptable amplitude limit for mild surge (Aretakis et al., 2004; Kyrtatos and Watson, 1980). In practice, a safety surge margin can be applied on the operating map to avoid surge occurrence during engine transient: the acceptable minimum operating flow is increased compared to the surge line measured on gas stand (typically 8 to 10%). However, even the small-amplitude fluctuations due to mild surge increase noise levels and vibrations. Hence, the detection, prediction and prevention to these phenomena are of great importance. The detection of precursors of these phenomena is used in active control in order to prevent harmful operating conditions. The use of blow-off (or by-pass) valve at the compressor exit is a simple common surge control: it relieves pressure when the throttle is lifted and the mfr is quickly decreased. More generally, the detection of unstable operation is usually achieved using aerodynamic sensors such as fast response pressure sensors, microphones, hot wires (Aretakis et al., 2004) or temperature sensors near the inducer (Andersen et al., 2008). These methods are often intrusive or in contact with the flow and are difficult to use in an automotive environment. Active control of surge includes implementation of a close coupled valve which is controlled along with the throttle valve (Gravdahl and Egeland, 1997; Bartolini et al., 2008), loudspeaker or a moving wall inside the plenum (Pinsley et al., 1991).

To avoid the use of active control because it adds cost and complexity, passive solutions to surge have been proposed, including inlet guide vanes (Rodgers, 1991); negative preswirl device in a 90° bend (surge line improvement at the expense of efficiency at high flow) (Galindo et al., 2006); and casing treatment with grooved shroud at the impeller tip leading edge (significant flow stabilization past the surge line, up to doubling the range) (Amann et al., 1975). Another solution is the use of a bleeding slot on the shroud wall above the impeller's inducer, which enables flow recirculation from the blades into the incoming air through a port channel cavity. At low mfr, flow is recirculated through the slot whereas at high mfr, the slot acts as an additional inlet increasing the inlet cross-section. Several studies have shown that the bleed slot improves the surge line reducing the minimum flow to about 80% of its value with less than one point efficiency penalty (Fisher, 1988; Yamaguchi et al., 2002). It is believed that by introducing an inlet recirculation casing treatment, unstable structures formed within the blades can be relieved through the port channels and mixed upstream of the wheel with the incoming flow, which in turn stabilizes the operation of the compressor, especially at low mfr.

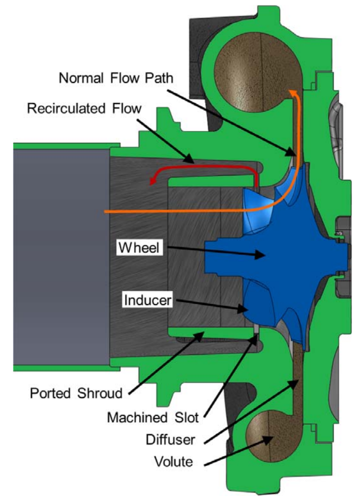


**Fig. 1.** Section view of the compressor.

## 2. Experimental rig

All the experiments presented here were carried out in the turbocharger test rig of the Gas Dynamic and Propulsion Laboratory at the University of Cincinnati. The turbocharger used for the experiments was manufactured by Honeywell Turbo Technologies with variable nozzle turbine (model GT40) designed for application in heavy duty truck diesel engines. The compressor impeller has an exducer diameter of 88 mm and a trim ratio of 56. It contains 10 full blades with 25° of backsweep angle from radial at the discharge.

The compressor housing features an inlet recirculation casing treatment with a ported shroud supported by four ribs that are positioned circumferentially, but not equidistant. Fig. 1 presents its geometry and the basic functioning of the device. This design is used to reduce the risk of high cycle fatigue of the impeller blades and results in four ported shroud cavities of different sizes connecting the compressor inlet to the radial slot machined on the shroud in the inducer region. The position of the ribs can be seen on the front views in Figs. 5 and 7. More details on the geometry can be found in Gancedo et al. (2013).

In order to study the impact of the ported shroud design on the compressor behavior, two configurations using the same compressor housing were studied: the regular casing with open bleed slot (OS case) and with the slot sealed with silicon to simulate a compressor with no recirculation (CS case).

As shown in the schematic in Fig. 2, the facility is operated in an open circuit driving the turbine with pressurized air. Control of the rotational speed (rpm) is achieved by controlling the turbine mfr by adjusting an electrically driven throttle valve through a PID control loop. The air entering the turbine is preheated by two electric heaters (with respective powers of 72 and 96 kW) mounted in series, which allow maintaining the inlet air temperature at 450 K. A closed-loop oil circuit provides pressurized lubricating oil to the rotating assembly within the center housing. The compressor mfr and outlet pressure are set by adjusting the opening of an electrically controlled V-ball valve mounted on the exhaust pipe approximately 2 m downstream of the volute exit. For the measurements presented in this paper, the compressor inlet was extended with a 430 mm long straight pipe. The turbine and compressor exhausts are connected to an oil particle condenser to remove lubricating oil residuals from the airflow before