

Investigation of Compressor Whoosh Noise in Automotive Turbochargers

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ABSTRACT

With swelling gasoline prices, automotive OEMs have taken different approaches to improve vehicle fuel economy. One trend is to down-size the engine and to add turbo charging. One of the challenges in utilizing the turbocharger in passenger cars is to control the added NVH issues associated with this hardware, especially for the North American market where turbocharger use is scarce in gasoline engines.

In this paper, the authors review an investigation on turbocharger related "whoosh" noise on a V6 engine. The whoosh noise, also called surge noise, is caused by the compressor working at or near surge conditions. Whoosh noise is a broad frequency band flow noise typically found during throttle tip-in conditions, but sometimes found even at steady state driving conditions.

The root cause of whoosh noise and the detection methods are discussed in this paper. The countermeasures to reduce whoosh noises are also discussed. These countermeasures are focused on both the excitation sources and the paths. The measures to reduce excitation source include altering the compressor trim size, improving flow conditions at the compressor inlet and engine system calibration. The measures to attenuate the paths include adding air inlet resonators on both the low and high pressure sides of the compressor. Some upfront design criteria needed to avoid whoosh noise are also discussed in this paper.

INTRODUCTION

There are two kinds of whoosh noises in turbocharged engines. One is encountered during throttle pedal tip-in maneuvers when the turbocharger speed increases in a relatively short period of time. This kind of whoosh noise sometimes happens at steady state too when the turbocharger speed is constant. The other noise occurs during abrupt throttle pedal tip-out when demanded air flow from the engine goes to zero. For both cases, the root cause of the noise involves turbocharger compressor surge. In this paper, we will only focus on the investigation of the whoosh noise during throttle tip-in maneuvers.

Evans et al. [1] have reported tip-in whoosh noise investigations on European Diesel engines. They have defined the marginal surge region of the compressor map and have proven that working the compressor too close to the marginal surge region is the root cause of the tip-in whoosh noise. In their study, they investigated improving the surge margin through the use of various size compressors and altering the flow conditions at the compressor inlet.

One of the reasons turbocharged engines get more and more whoosh noise is due to the demand for higher torque at low engine speeds. Lower engine speeds mean lower air flow. Additionally, higher torque demand means higher manifold pressure, which is equivalent to a higher pressure ratio across the compressor. The combined effects of low air flow and high pressure ratio

push the compressor working line closer to the surge line or in the marginal surge region. On the other hand, the higher power requirement at high engine speed drives the maximum turbocharger speed close to its own speed limit known as the choke region. These operational limits typically prohibit the possibility of resizing the compressor to meet both low end and high end demands concurrently.

TURBOCHARGER WHOOSH NOISE

The turbocharger whoosh noise studied here was first reported on a prototype vehicle. An extensive investigation was subsequently conducted on a powertrain dyno in a semi-anechoic cell configured according to SAE standards as shown in Figure 1. The induction orifice is at the left side of the powertrain and was found to emanate significant whoosh noise to the vehicle interior. All the reported noise and comparisons are based on the left hand 1-meter microphone known as PEL-X.

Figure 2 shows the color map of radiated noise measured during a full load run-up. The whoosh noise is shown in the engine speed range 1500-3000 rpm where a broad frequency range is highlighted. Further investigation reveals that the critical frequency band for the subject whoosh noise is from 5-7 kHz. Pressure pulsation measured concurrently at the compressor inlet confirmed this critical frequency range. Figure 3 is the overall radiated noise and indicated whoosh noise in the 5-7 kHz band.

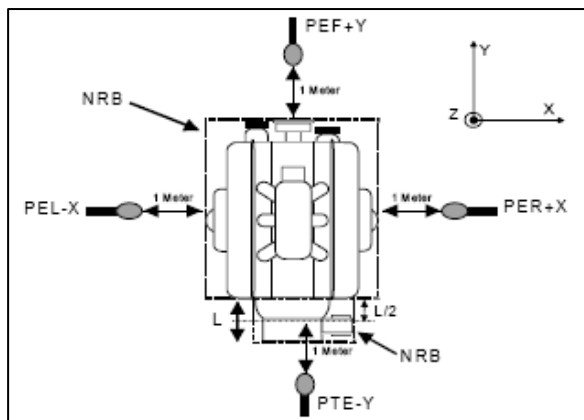


Figure 1: The standard Powertrain setup for whoosh noise investigation.

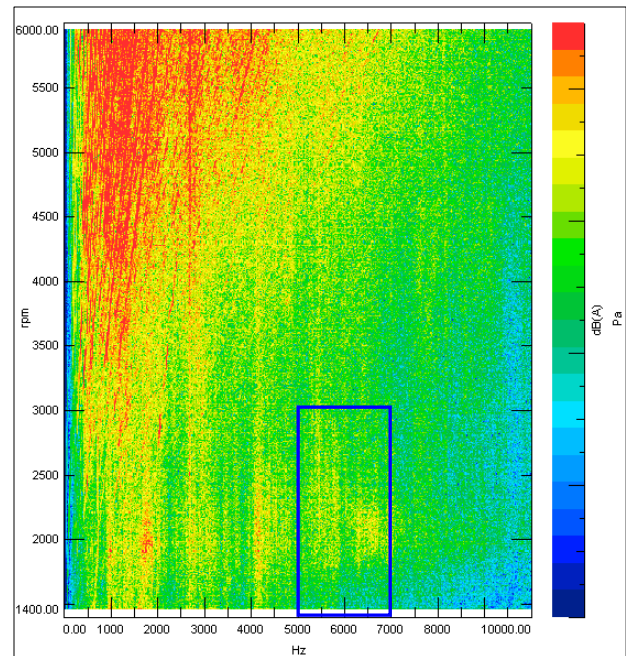


Figure 2: Color map of radiated noise

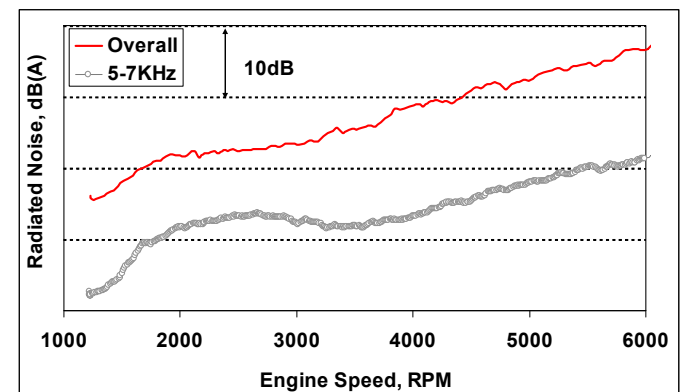


Figure 3: Overall radiated noise and whoosh noise in 5-7 KHz

ROOT CAUSES OF TURBOCHARGER WHOOSH NOISE

As discussed above, the whoosh noise discussed here is related to compressor surge or marginal surge. The first step in the root cause analysis is to produce the compressor working line. Figure 4 is the compressor working line at full load. The whoosh noise happens at the low air flow region as indicated. This confirms that the compressor working line is too close to the surge line. In other words, there is a lack of margin between the two.

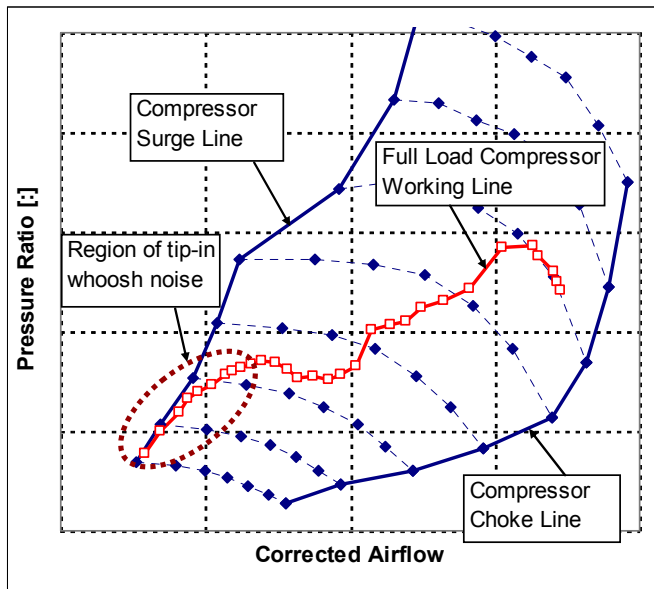


Figure 4: Compressor working line at full load conditions

The pressure pulsations at both the compressor inlet and outlet are also measured to better understand the whoosh noise excitation. Figure 5 shows the pressure pulsation measured at the compressor inlet during the full load run-up. The strong pressure pulsation seen in the 5-7 kHz frequency band between 1500-3000 rpm correlates very well to the whoosh noise observed in Figure 2.

Sometimes performance engineers and NVH engineers have different views on the surge phenomenon. From a performance perspective, surge exists only when engine performance is affected. However, proximity between the compressor working line and surge line may be enough to experience unacceptable noise issues as shown here. Therefore, it is not sufficient to define the "surge phenomenon" in the strictest sense using this proximity measurement. An alternative metric is needed to better define the surge or marginal surge for NVH.

It's very well known that the local air temperature at the compressor inlet will increase during the compressor surge. Anderson et al. [2] have reported using temperature sensors on the turbocharger test rig to record this temperature rise at the compressor inlet. They have mapped the temperature rise over the entire compressor map. The results show that the closer the compressor is working to the surge line, the higher the temperature rise. Soh et al. [9] also used temperature rise at the compressor inlet to define compressor surge during the tip-out whoosh noise investigation.

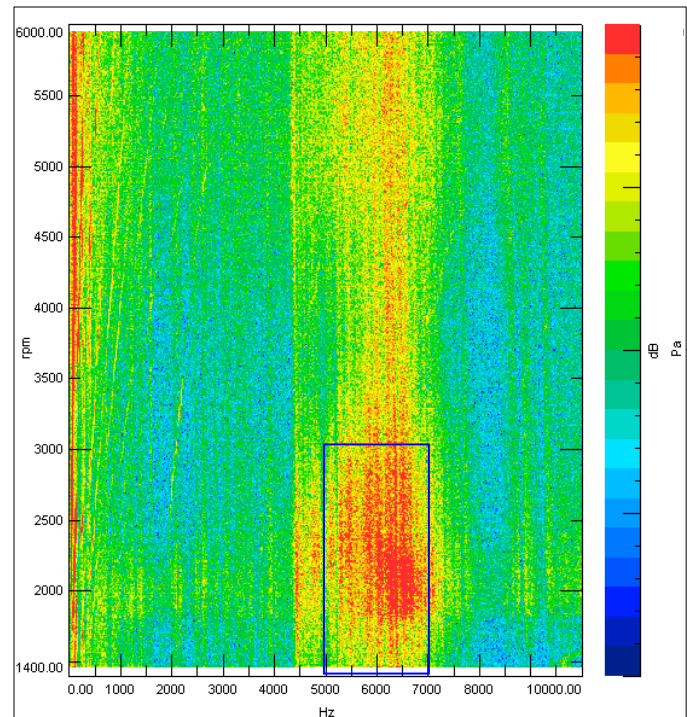


Figure 5: Pressure pulsation measured at compressor inlet during WOT conditions.

The same concept is used here to help define NVH related surge and establish correlation between whoosh noise and temperature rise at the compressor inlet. A type K thermocouple is installed inside the compressor inlet about 10-15 mm from the compressor blade tip. Figure 6 shows a schematic of the thermocouple inside the compressor inlet and the measured temperature during engine full load operation along with the whoosh noise. It clearly shows that, in the whoosh noise region, the air temperature at the compressor inlet rises due to surge or marginal surge. Figure 7 shows the pressure pulsation (5-7 kHz) measured at the compressor inlet vs. temperature rise. The compressor surge or marginal surge results in both air temperature rise and pressure pulsation, which is the root cause of the subject whoosh noise.

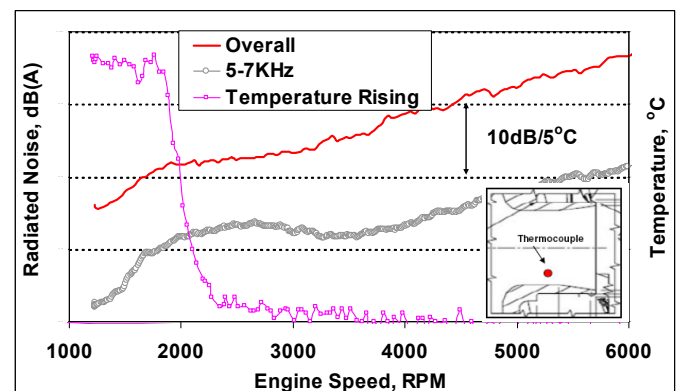


Figure 6: Temperature rise at compressor inlet vs. whoosh noise during full load run-up.