

Turbocharger Test Bench Extension for Acoustic Measurements at Cold Environment Conditions

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ABSTRACT

Acoustic measurements, especially interesting for new bearing concepts such as ball bearings, are an important part of the evaluation of turbochargers. Typically, acoustic benchmarking is done at standard conditions, neglecting possible negative effects of very low temperatures, as they might be encountered in real-world applications.

For realistic turbocharger measurements at cold environment conditions down to -10°C , special adjustments to the turbocharger test bench have been made. This article introduces a soundproofed climate chamber built in the turbocharger test bench which is able to achieve low component and oil supply temperatures while still providing adequate conditions for acoustic measurements.

In the first part of the paper, the concept of the acoustic climate chamber is presented. Layout calculations are shown as an indicator for the performance of the acoustic and thermal isolation. For the second part of the paper, acoustic measurements with different turbochargers have been made at the following temperatures: 20°C , 10°C , 0°C , -5°C and -10°C . The acoustic benchmarking included both air borne and structure borne sound as well as two distance sensors to measure the orbital movement of the turbocharger shaft at the compressor side. The experimental procedures are being described in detail.

Two aerodynamically identical turbochargers, one representing typical journal bearings and the other one representing a ball bearing concept, were examined. Both show a quite different acoustic behavior concerning the body temperature. While the emitted sound pressure levels of the journal bearing seem to be almost independent from the temperature, the measurements with the ball bearing do show a strong influence towards high sound emissions at low temperatures.

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INTRODUCTION

Most of today's modern, fuel efficient automobile engines use exhaust gas turbochargers. While aiming for higher efficiencies of these components, many different approaches are being taken into consideration such as new bearing concepts. The transition from journal bearing to ball bearing offers magnificent potential for lower friction loss [1, 2]. At the same time, in many cases the generated noise level of ball bearing turbochargers exceed the limits for series-production. Consequently, in addition to normal performance mapping, acoustic measurements play a decisive role in turbocharger benchmarking as well.

Typically, acoustic benchmarking of turbochargers within a turbocharger test bench is done at standard conditions, using acceleration sensors mounted to the housing. However, these conditions might be quite different from situations encountered in real world environments. Internal benchmarks of OEMs like VW indicate that the aforementioned ball bearings for turbochargers show high acceleration levels, especially at low temperatures below the

freezing point. Moreover, acceleration sensors only give you the structure borne sound, which can differentiate from the air borne sound received by the human ear.

As an approach to provide a more realistic environment for acoustic turbocharger benchmarking, this work documents the development and construction of a soundproofed climate chamber for a turbocharger test bench, as well as test protocols and measuring results for low temperature measurements down to -10°C . Acoustic data has been collected using acceleration sensors, microphones and eddy current distance sensors in order to examine the correlation between air borne and structure borne sound as well as the movement of the rotating shaft as a source of sound.

CONCEPT

The mentioned issues concerning acoustic measurements in turbocharger test benches inspired the studies reviewed in this paper. In order to investigate the acoustic behavior of turbochargers at low temperatures, the following goals for the measurement conditions have

been defined: a) The ambient air temperature and, as a result, the component temperature can be conditioned down to -10°C for the start of the experiment¹. b) The inlet flow temperature of the oil, supplying the turbocharger, can be kept at low temperatures down to -10°C for the whole duration of the experiment. c) The measurement setup allows air borne acoustic measurements using microphones while keeping any disturbances from the test bench machinery at a relatively low level compared to the emitted sound of the turbocharger².

The approach chosen to create the aspired measuring conditions was to build a climate chamber around the turbocharger within the test bench, providing sufficient thermal and acoustic isolation. For acoustic measurements in a closed room, other challenges than just the isolation have to be taken into consideration: Most importantly, the room should be as big as possible, due to its cut-off frequency³. Moreover, reflections at the walls should be minimized by using dampers to prevent echoing. Beside requirements related to the acoustic measurements, also the following aspects had to be respected for the concept and the construction of the climate chamber: a) A modular design to provide flexibility for unknown future test subjects, b) transportability and low storage volume when not in use, c) overall cost of the construction and d) structural stability and safety.

Construction

Based on these requirements, the final construction of the climate chamber has the following specifications. The structure base is provided by a steel frame, consisting of a bottom part, 4 pillars and a top part (figure 1). The frame supports 3 wall elements on each of the six sides. All wall elements, except the three floor elements are identical and can be interchanged. The composition of the wall elements is similar to a typical drywall installation. Each wall element consists of two layers of 12.5 mm gypsum panel on the one side, 100 mm of mineral wool in the middle and another two layers of gypsum panel on the other side (figure 1). This established structure provides good noise dampening properties due to the high mass per area of the gypsum panels as well as thermal isolation due to the low coefficient of heat transfer from the mineral wool, at relative low costs. The wall elements are being held together by u-profile sheet metal. The vertically standing wall elements are individually secured by a steel crown on top of the ceiling wall elements. Each wall element has a mass of 50 kg which allows handling them with two persons. The mass of the whole chamber is approx. 1.5 t. The steel frame is supported by 8 pedestals, containing a viscoelastic layer to decouple external vibrations. Holes in the wall elements have been provided for turbine inlet and outlet, compressor inlet and outlet, coolant, oil and cable connections.

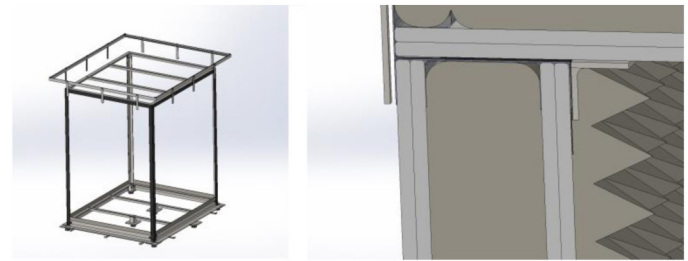


Figure 1. Left: Steel frame of the climate chamber. Right: Cross section showing the composition of a wall element.

Cooling Concept

An adjustable 5 kW (el.) separate cooling unit was used to supply coolant for the climate chamber. Inside, an air/water heat exchanger and a fan was used to cool down the air temperature. Moreover, a fluid heat exchanger was used to lower the oil temperature for the turbocharger. Both heat exchangers are connected in parallel with separate valves to adjust the coolant mass flow individually. Figure 2 shows the cooling concept of the climate chamber as a view from the top.

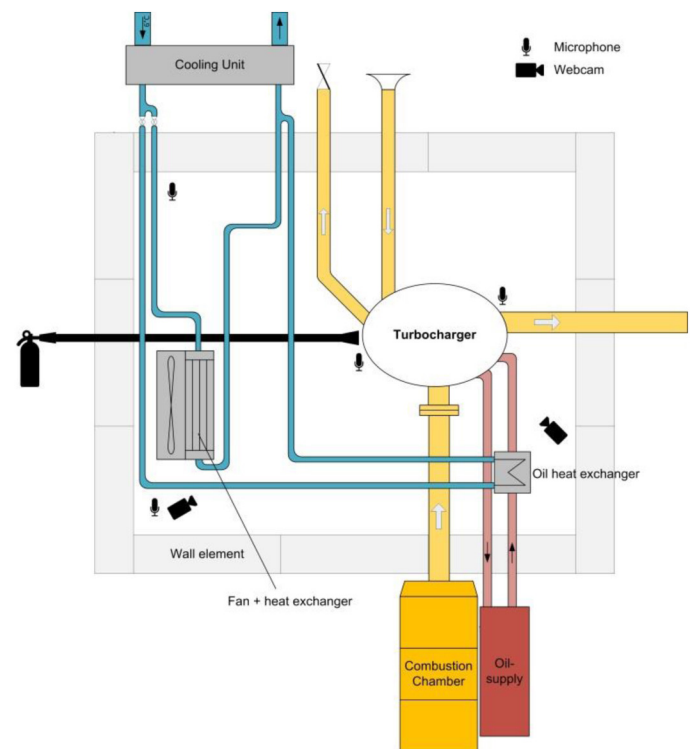


Figure 2. Schematic layout of the climate chamber including the cooling concept.

Acoustic Properties

One important part of developing the concept of the climate chamber was to look at different acoustic properties to be able to evaluate measurements of air borne sound using microphones. Following, a selection of the most important acoustic properties is being calculated.

1. It is expected that the component temperature will rise rapidly as the turbocharger starts running.

2. According to experience, the noise level within the test bench due to the compressor for the turbine mass flow as well as the oil supply pump can be described as very loud during normal turbocharger measurements.

3. The cut-off frequency f_c describes the lowest frequency which still can create a diffuse sound field within a closed room. Waveforms of lower frequencies cannot form properly since the wavelength is bigger than the room dimensions. As a consequence, measurements of amplitudes of frequencies below the cut-off frequency might be seemingly too low.

Reverberation Time

The Reverberation time can be understood to be the time span between turning off a source of sound and the sound pressure level in the room dropping by 60 dB. For acoustic measurements, a low reverberation time is desirable. N. Eyring gives the following equation for the reverberation time RT_{60} , as an enhancement of the original formula from W. C. Sabine, as a function of the room Volume V , the Wall surface area S and the material and frequency dependent absorption rate α [3].

$$RT_{60} = 0.163 \cdot \frac{V}{-S \cdot \ln(1 - \alpha)} \quad (1)$$

The calculated mean reverberation time for the climate chamber concept equals $RT_{60, \text{mean}} = 0.34$ s.

Schröder frequency

The Schröder frequency f_s describes a cut-off frequency for room acoustics. Waveforms of lower frequencies cannot form properly since the sizes of the wavelengths exceed the room dimensions. Below the Schröder frequency, the specific room modes dominate the acoustic behavior [4].

$$f_s = 2000 \cdot \sqrt{\frac{RT_{60}}{V}} \quad (2)$$

The calculated Schröder frequency for the climate chamber concept equals $f_s = 567$ Hz.

Reverberation radius

The critical distance from a source of sound, at which the sound pressure level of direct and reverberant sound are equal, is called reverberation radius d_c . It can be calculated by the approximation formula by W. C. Sabine [5].

$$d_c = 0.057 \cdot \sqrt{\frac{\gamma \cdot V}{RT_{60}}} \quad (3)$$

Assuming the degree of directivity of the sound source γ being 1, the calculated reverberation radius for the climate chamber concept equals $d_c = 0.20$ m.

Thermal Properties

The thermal isolation properties of the climate chamber have been estimated using the standard heat transfer equation [6].

$$\dot{Q} = \frac{\lambda_i}{s_i} \cdot A \cdot \Delta T \quad (4)$$

The individual coefficients of thermal conduction λ_i , the corresponding material thickness s_i as well as the surface area A have been applied to this equation for a temperature gradient of 40 K. The calculated thermal loss for all big surface areas, only considering gypsum panel and mineral wool, add up to $\dot{Q}_{\text{wall}} = 231$ W. In addition to that, the steel frame and the sheet metal surrounding the wall elements act as thermal bridge and thus have to be included as well. Although providing a much smaller cross section area, the calculated thermal loss of $\dot{Q}_{\text{metal}} = 1213$ W even exceeds the loss over the wall isolation. Combined, the theoretical thermal loss is around 1.5 kW. Even considering some air leakage between the wall elements, the power of the given cooling unit seems sufficient, providing 15 kW cooling power (while taking 5 kW el. power). Finishing this section, it is mentioned that an adequate heat exchanger and fan for the cooling concept of the climate chamber had to be found.

Safety

All materials used in the climate chamber, including the pyramid profiled foam, are at least flame retardant in accordance with building material class B 1 of DIN 4102-1. In addition to the CO₂ fire-extinguish system of the turbocharger test bench, a separate system was installed to release CO₂ directly into the climate chamber in case of fire. This is necessary because there is no gas exchange between the air within the climate chamber and the surrounding test bench.

In this study, no experiments were done using the combustion chamber, although the climate chamber is technical capable running turbocharger measurements at standard conditions ($T_3 = 600$ °C). As a result, the highest temperatures occurred at the compressor outlet, reaching $T_{2, \text{max}} = 100$ °C.

Installation in the Test Bench

The climate chamber was built and installed into the turbocharger test bench. A photograph of the finished test setup with two wall elements removed is shown in Figure 3. As can be seen in the picture, with a size of 1.7 m × 2.0 m × 2.30 m (length, width, height) the climate chamber used all available space between combustion chamber and surrounding tubing/walls.

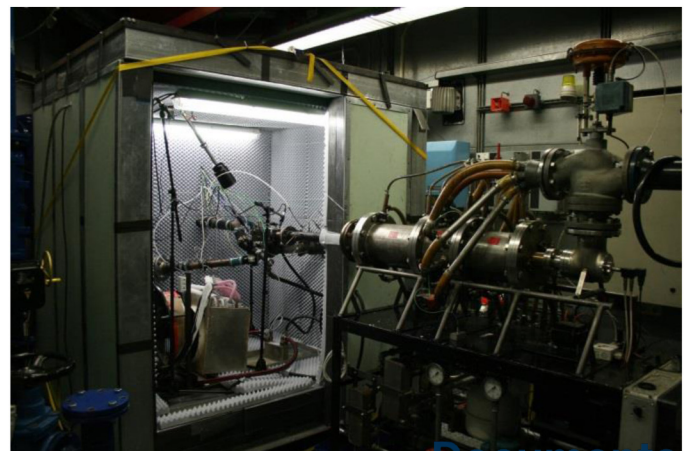


Figure 3. Turbocharger test bench with climate chamber.