Investigation of flow-acoustic interaction in automotive turbocharger

R. Kabral¹, M. Åbom¹
¹CCGEx, MWL, KTH Royal Institute of Technology, Teknikringen 8, SE-100 44, Stockholm, Sweden e-mail: kabral@kth.se

Abstract
In IC engine design, the surge condition of a turbocharger is a well-recognized phenomena. As the resulting global fluctuation of mass flux in the intake system is hazardous, the implemented safety margins are large. In order to reduce such safety margins and employ turbochargers more efficiently, it is of interest to investigate acoustic fields as a possible surge triggering mechanism. Regardless the increasing relevance of this topic today, only few publications exist addressing the acoustics of turbochargers from the perspective of surge prediction and triggering.

In the present paper acoustical properties of an automotive turbocharger are experimentally studied at the limit of stable operation as well as under normal operating conditions in the unique CCGEx test rig at KTH. The full two-port data including passive and active parts is determined and utilized to investigate the possible coupling effects between unstable flow and acoustic fields. The local flow instabilities, occurring at the limit of globally stable operation, can interact with the acoustic field and amplify incident sound waves which eventually can lead to an unstable situation and surge. This effect can be studied from the passive two-port data. In addition the active data can be used to find the occurrence of compact correlated sources in the compressor such as rotating stall a pre-cursor of surge.

1 Introduction

All IC engines for road vehicles in Europe has to comply with emission regulations known as Euro 5 and 6 [1] starting from 2015. Therefore, in IC engine design today, the implementation of superchargers for efficiency reasons is essential. This concept is well known as the downsizing, in passenger car industry, or rightsizing of the IC engine, in the truck industry. In former case, turbochargers are often complemented by directly driven compressors. Such configuration is capable of delivering the needed high pressure charge air in a wide mass flow range, and moreover, the transient response of the unit will be noticeably improved. Nevertheless, these systems are relatively sophisticated, and therefore, not a robust enough solution for the truck industry. In addition, as the transient response time of a truck engine is less important, the efficient implementation of the turbochargers are of interest instead. A simplified sketch of such a turbocharged IC unit layout is presented in the following Figure 1.
The mass flux of the turbo-compressor is limited by choked flow and surge conditions. At the compressor surge, where the mass flow fluctuations are global and become hazardous to IC unit components as well as to the compressor itself, the mass flow safety margins can be as high as 20%. In order to more efficiently use the compressor, the better understanding and prediction of surge condition is of essence.

### 2 Experimental setup

The facility for acoustic testing of turbochargers at KTH CCGEx was established in 2008 [3] and has since then been continuously further developed. In the rig, turbochargers are operated under stationary conditions while the acoustic Two-port data is being determined. The capability of the facility is such that it can cover all the operating range of a typical automotive turbo-compressor. The photo of the test-rig at KTH CCGEx is presented in the Figure 2.

In [5] Kabral et al. recently successfully determined the full acoustic Two-port data (passive and active properties) of an automotive turbo-compressor at five operating points (OPs). The measured physical quantities determining these operating points are given in Table 1 and the graphical representation on the compressor map is shown in Figure 3.
Table 1: Operating conditions of the turbocharger [7].

<table>
<thead>
<tr>
<th>Pressure Ratio, 1</th>
<th>Corrected Mass Flow, kg/s</th>
<th>Rotational frequency, RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>OP 1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>OP 2</td>
<td>1.28</td>
<td>0.054</td>
</tr>
<tr>
<td>OP 3</td>
<td>1.85</td>
<td>0.119</td>
</tr>
<tr>
<td>OP 4</td>
<td>1.37</td>
<td>0.126</td>
</tr>
<tr>
<td>OP 5</td>
<td>1.71</td>
<td>0.050</td>
</tr>
</tbody>
</table>

Figure 3: Operating points of the turbocharger on the compressor map [5].

3 Method

In general, the flow field in a turbo-compressor can affect the incident sound field in two ways. The incident acoustic power can be dissipated in small scale turbulence or amplified by the modulation of incident sound waves in case of flow instabilities. In [5] the existence of such amplification was investigated at five OPs of a turbo-compressor (See Tab. 1 and Fig. 3).

As all aero-acoustic coupling effects are included in the passive part of the experimental Two-port data, the effects were possible to study by setting up the acoustic power balance over the turbo-compressor and normalizing the incident sound power to 1W. Moreover, to include all the possible phase and amplitude relations between the inlet and outlet of the turbo-compressor, eigenvalues of the so called sound power scattering matrix were determined. These eigenvalues are representing the minimum and maximum potential amplification of incident sound power.

4 Results

The resulting maximum possible amplification spectrums are plotted in the Figure 4, where it can be observed that the maximum potential amplification spectrums of five OPs that were studied are negative across the frequency range i.e. that there is no net amplification of incident sound power. The curve corresponding to the OP5 (Fig. 4) has a distinguishable peak at 900 Hz, which is not observable in case of all the other OPs. Furthermore, the frequency of this peak was found in [5] to correspond to the shaft rotational frequency with a multiplier of 0.45, where often the rotating stall flow instability is observed.
In perspective of acoustic triggering of a surge condition, the peak at 900 Hz is not relevant since the overall dissipation still dominates over the local amplification. What is relevant, is the very small dissipation at the low frequency range (Fig. 4) i.e. the compressor is then very sensitive to the acoustic perturbations at these frequencies. Moreover, if the boundaries of the compressor in the complete system are causing high reflections as well, it is believed that the system can be driven to the surge by corresponding incident acoustic waves.

![Figure 4](image-url)

Figure 4: The difference between scattered and incident sound power normalized with the incident (1 W) at five operating points. Positive values mean amplification of sound by vortex-sound effects (See Tab. 1) [5].

The active part of the full Two-port data of a turbo-compressor gives the reflection free sound generation in both junctions. In [5] this data was for the first time determined for the turbo-compressor working under realistic operating conditions. The spectral densities of the generated sound are plotted in Figure 5.

![Figure 5](image-url)

Figure 5: The generated sound pressure level at both branches of the compressor at different operating conditions (See Tab. 1) [5].

When the sound generation by rotating machines is considered, the most well-known and dominating tone is expected always at the blade passing frequency. Therefore, the common misconception is that, in the 0th duct mode or plane wave frequency range, the sound generated by the turbo-compressor is consisting only of broad band flow noise. It was shown in [5] that additional tonal contributions exist in the generated sound spectra (Fig. 5). Furthermore, it was observed that the frequency of these high level tones correspond to the shaft rotating frequency harmonics and the level is linked with mass flux. Also the level, in general, was
found to be lower at the inlet. All these observations led to the conclusion that these tones are caused by transonic flow in the impeller vanes inducing shock waves interacting with the diffuser [5].

In addition, the overall level of the generated sound (Fig. 5) is already relatively high at all OPs but will be noticeably increased (~15 dB) across all the frequency range when operating close to surge. Also the low frequency sound, which can trigger a strong surge, is generated by the machine itself.

5 Concluding remarks

In the present work the investigation of flow-acoustic interaction in a turbocharger based on experimental data was presented. It was found that the minimum possible dissipation at low frequency range is approximately zero and the amplitude of reflection free sound generated in the low frequency range is high i.e. that in case of suitable boundary conditions, the acoustic energy in the system will grow which eventually can lead to strong surge.

Still it remains to investigate further the combination of excitation needed for the minimum possible dissipation of acoustic power and by experimentally providing such boundary conditions proving the possibility to trigger surge by means of acoustic field. The active part of the data can further be used to compute the coherence between the up- and downstream sides which also should be studied.

Acknowledgements

The financial support from European Union (7th Framework program) through Marie Curie actions initial training network FlowAirS (www.flowairs.eu) is greatly acknowledged.

References


