Development of a Reactive Silencer for Turbo Compressors

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Abstract: This paper describes the use of acoustic modeling tools for the development of a new concept of silencer to reduce the tonal noise radiated by a turbo compressor installation.
The new silencer concept is based on an array of resonators that replaces the absorption material in a conventional silencer. This makes the silencer very robust for high flow velocities and less sensitive for dust, whilst the performance is equal or better than the conventional silencer.
In order to cover a wide frequency range the resonators need to be tuned carefully to adjacent frequency bands. For this acoustic modeling with COMSOL's acoustic module has been used intensively.
In this paper the modeling is described, a comparison with test results is shown and the results of a calculation for a complete silencer is discussed.

Keywords: Acoustic silencer, resonator array, acoustic modeling, turbo compressor, pipe system.

1. Introduction

Turbo compressors can generate tonal noise in a frequency range of 1000 to 5000 Hz, which may cause nuisance in the environment. In extreme cases also damage of the compressor or pipe system has occurred. The cause of this tonal noise is the interaction between flow and rotating blades inside the compressor. The noise is transmitted from the compressor internals to the pipe system at suction and discharge and radiated from the pipe walls to the environment. As the wall of the compressor housing is very heavy, direct radiation off acoustic energy is small.
Because the allowable noise level for tonal noise is much lower than for broadband noise, it is important to reduce the magnitude of this noise source.
This noise source cannot be suppressed by changing the design of the compressor internals without consequences for the aerodynamic performance. Instead, a silencer is installed between the compressor and the pipe system. The silencer blocks the transmission of the noise to the pipe system where it can radiate from pipe walls and walls of other equipment, such as vessels and heat exchangers.

The silencer type that is often applied for this is the so-called absorption type silencer, which is a vessel that is partly filled with material that dampens, i.e. absorbs, acoustic waves. In order to achieve sufficient damping materials like glass or rock wool are applied. They consist of very thin fibres that are packed together and shielded with a perforated plate. In spite of this it has occurred that due to high flow velocities and vibrations the absorption material deteriorated and was blown out of the silencer into the pipe system where it caused all kinds of problems. Therefore a more robust design has been developed based on acoustic resonators that block the acoustic waves that come out of the compressor. As the resonators are made of solid material, it is obvious that the integrity of this silencer concept is of no concern.

For the prediction of the performance of this silencer concept the acoustics has been modelled by two approaches. First a one dimensional PULSIM model for the coarse design and thereafter a three dimensional model was used in COMSOL for fine tuning. A practical case has been used to make a realistic silencer design. The performance has been compared with a conventional silencer.

2. The silencer concept

2.1 A resonator array instead of absorption material

A conventional silencer consists of a large diameter pipe in which a bulk of absorption material is attached at the wall. Acoustic waves passing through the pipe are partially penetrate the absorption material, where they are

dissipated. This type of silencer is called absorption or dissipative silencer. To be effective the absorption material has to have a very fine structure. However, the finer the material, the more vulnerable it is for static and dynamic fluid forces. The material will deteriorate, the dampening will decrease and the material will eventually vanish into the connected pipe system.
Another approach is to use reactive elements that make use of gas inertia and compressibility, to build an acoustic filter that blocks the transfer from source to the connected pipe system. The filter consists of an array of resonators located in the wall of a pipe, similar to the absorption material of a conventional silencer. Groups of resonators are tuned for adjacent frequency bands such that the required (wide) frequency band is covered.

2.2 Implementation

The implementation of a resonator array is as follows: a certain profile is cut off from a plate, thereby forming a set of resonators that are tuned at the same frequency. See **Figure 1**. By stacking a number of plates (with separation plates in between) with adjacent frequency bands, a silencer can be made that covers a wide frequency band.

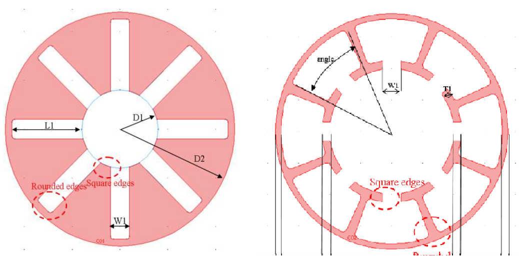

Figure 1. Resonator plates: quarter wavelength (left) and Helmholtz (right) type resonators.

An important difference with the absorption silencer is that the resonators block the transfer of acoustic waves. This means that acoustic energy is reflected back to the source and therefore increases the acoustic level at the source. However, the great advantage of the concept is the robustness and the relative insensitivity for dust, which makes the concept suitable for all applications with compressors.

2.3 Acoustic design aspects

As the new silencer concept has to function for high frequencies, the dimensions of the resonators will be small and a large number of resonators has to be used. On the other hand the flow area has to be as large as possible in order to keep the pressure drop to a minimum. In order to maximise the effect of the resonators, the flow area has been split in a number of smaller parallel channels. One of the main goals is avoiding the appearance of 3D acoustic modes above the corresponding cut-off frequency. Nevertheless on the high frequency range, three dimensional effects occur.

2.4 Proof of concept

The silencer concept with resonators has been demonstrated by means of a laboratory test with scale test sections. The transmission loss has been measured and compared with calculated results.

3. Use of COMSOL Multiphysics

In order to shorten the design procedure, as a first step a one dimensional (1D) model is made using PULSIM. With the 1D model the tuning of the resonators is designed such that the required frequency range is covered as well as possible. In the second step, the fine tuning is done with a three dimensional (3D) model.
For the 3D modeling of the test section and a complete silencer the acoustic pressure module of COMSOL has been used. Extensive scripting has been used to generate the geometry of each model.
An important aspect of the silencer is the damping, which determines the width of the resonator absorption band. This damping depends on the flow velocity through the silencer. As it was not known how to model the damping caused by the flow, it could not be included in the 3D model.

4. Test of a small silencer

As a proof of concept and to determine the effect of pressure loss a small section was tested. The test section consisted of a stack of plates with various resonators. Each plate has a number of resonators tuned at the same frequency. The coverage of a frequency range could be made by selecting plates tuned for specific frequencies. Two types of resonator arrays have been tested; one with so-called quarter wavelength resonators (QW) and one with Helmholtz resonators (HH). See Figure 1. A number of plates is shown in Figure 2 and the stack installed in the test rig in Figure 3.

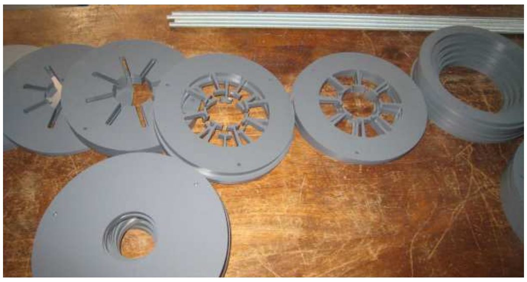

Figure 2. Resonator plates for the test section.

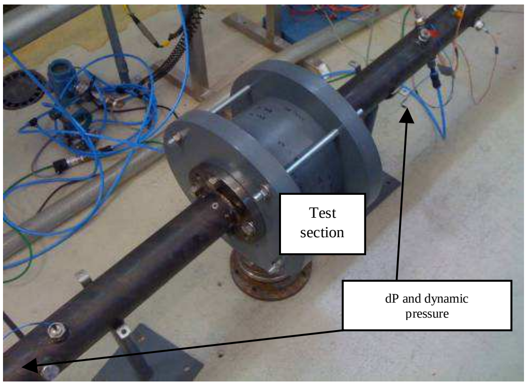

Figure 3. Silencer section installed in the test rig.

The test rig consists of an acoustic source, an inlet and outlet pipe terminated with a silencer. At inlet and outlet pipe a Two Microphone Method (TMM) set-up was applied to measure the ingoing, reflected and transmitted acoustic waves.

Both a 1D and a 3D model was made and the results are compared with the measured Transmission Loss (TL).

The results are shown in Figure 5 and Figure 6. For the QW resonators both 1D and 3D models predict the resonance frequencies rather accurate. As expected the 3D model is more accurate for the higher frequencies. However, because the 1D model includes damping it reproduces the height of the peaks more accurately. In the 3D model the peaks are too high. For frequencies above approximately 2500 Hz the TMM give erronous results due to transversal modes in the inlet and outlet pipe.

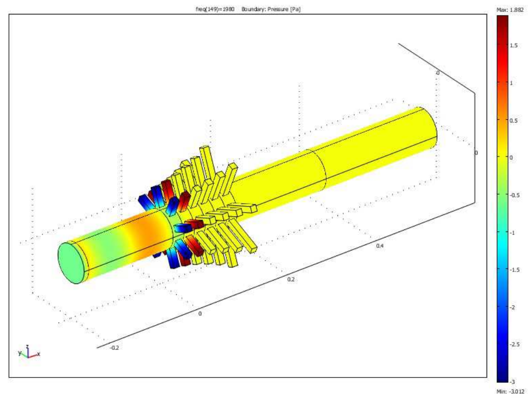

Figure 4. Typical result of a COMSOL calculation for 1980 Hz. This shows that the first two rows of resonators are active.

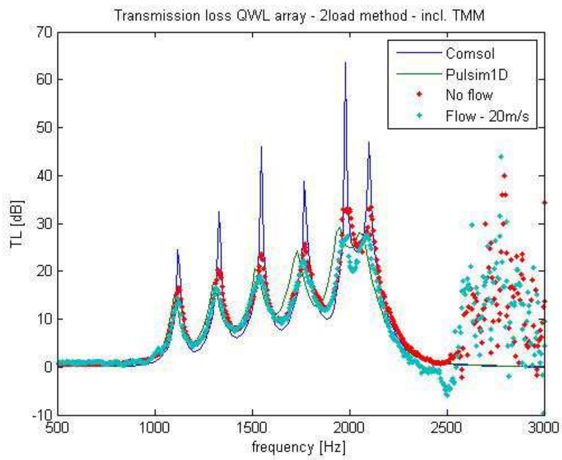

Figure 5. Results for the QW resonator array.

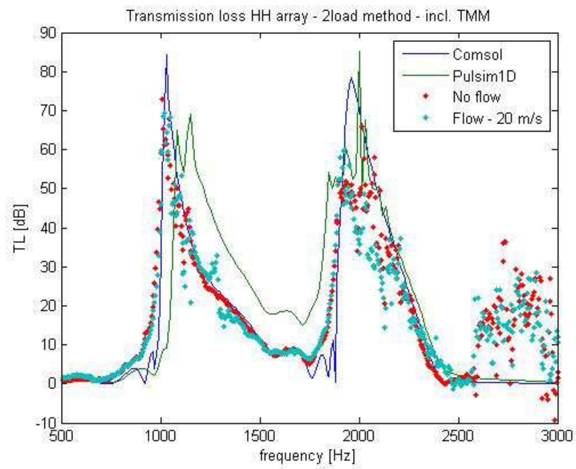

Figure 6. Results for the HH resonator array.

For the HH resonator array the 1D model over predicts the performance of the silencer and the 3D model is more accurate. Still the minimum performance at approximately 1800 Hz is still satisfactory. This can be improved by bringing in additional HH resonators tuned at 1600 Hz.

5. Design for a real case

A silencer has been designed for a real compressor in order to get realistic dimensions for determining the manufacturing costs.
The silencer has been designed for the discharge line of the compressor, which has an inner diameter of 682 mm.
The silencer is required to have a minimum Insertion Loss (IL) of 5 dB in the frequency range from 1000 to 3000 Hz. This wide frequency range is required because the compressor runs at a varying speed and both the Blade Passing Frequency (BPF) and two times BPF have to be suppressed.
In order to keep the pressure loss to a minimum, the flow area of the silencer has to be equal to the area of the discharge pipe. The silencer consists of a pipe with a larger diameter than the discharge line. In the pipe a central body is installed with resonators extending to the center. Also resonators are placed at the wall of the pipe. Seven splitter plates have been placed in radial direction to avoid circumferential modes.
The silencer consists of QW resonators in front for the high frequency range and HH resonators at the rear of the silencer for the low frequency range. See Figure 7.

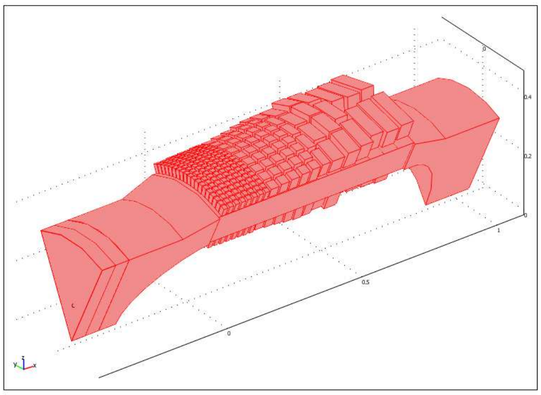

Figure 7. One segment of the silencer with QW and HH resonators.

As all segments are the same only one segment had to be modeled, which greatly reduces computer time.
The tuning of the resonators have been done with a 1D model. Next a 3D model has been used to evaluate the 3D effects and it appeared that additional tuning was necessary as is shown in Figure 8**.** The design was optimized after the first results to finally attain the desired performance.

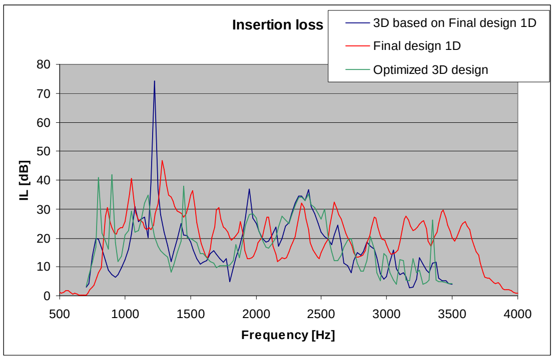

Figure 8. Results for the 1D and 3D optimisation

In the final 3D design the IL is larger than 10 dB for most of the frequencies of interest. This is well above the minimum of 5 dB. This margin is required to cope with the effect of impedance of the compressor stage and the resonances upstream of the silencer.

6. Conclusions

Numerical modeling and small scale tests have been performed to design a reactive silencer for centrifugal compressors. For a first design 1D modeling is sufficiently quick to study the effect of the main parameters. However, 3D effects can easily disturb the carefully designed characteristic. Therefore 3D modeling is necessary.
The COMSOL acoustic module has been an excellent tool for the design. For the generation of the model scripting tools have been used that saved much time.
The reactive silencer concept has proven to be feasible even for wide range of frequencies.

7. References

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