APPLICATION OF NUMERICAL MODELLING METHODS TO THE DESIGN OF SILENCERS

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1 INTRODUCTION

Many machines and industrial production facilities require silencers to reduce the noise transmission through intake or exhaust ducts, with examples ranging through motor car exhausts, industrial silencers and aeroengine intake and exhaust liners. Traditional silencer design methods use analytical or transmission matrix acoustic models, followed by empirical development work to produce robust designs. However, these methods are not suitable for designing silencers with unusual chamber shapes and layouts and are generally not accurate enough to predict backpressure, which may be an important design constraint.

Numerical modelling methods developed for aeroacoustics problems are now well established for application to a wide range of engineering problems. After a brief introduction to the main types of silencers, this paper summarises traditional analytical methods versus modern numerical modelling and illustrates the computational process applied to three case studies.

2 REACTIVE AND ABSORPTIVE SILENCERS

Silencers are divided into two types: reactive and absorptive. Reactive silencers (Figure 1) use geometrical duct variations to block the sound transmission, such as expansion chambers or Helmholtz resonators, which are particularly efficient at certain frequencies. Absorptive silencers (Figure 2) use special materials or honeycomb structures to absorb the incident wave and convert acoustic energy in heat. The latters are more effective over a wider range of frequencies and generally provide a lower pressure loss. Generally, reactive silencers are mainly used for low speed flows at low frequency, as in the automotive sector, while absorptive silencers, also known as liners, are mainly used in the aerospace industry where high speed flows are involved. However, in reality many silencers display a mix of reactive and absorptive characteristics, depending on frequency

Different properties characterize the silencers depending on their type. Reactive silencers are defined based on the number of chambers and their expansion ratio and volume. Absorptive silencers are defined using the acoustic characteristic of the packing material, such as flow resistivity, or the complex acoustic impedance of the liner, which is the ratio between the acoustic pressure and the particle velocity at the duct wall, $Z = R+iX$, where R is resistance and X reactance. Acoustic impedance is generally normalised using the product of fluid density and speed of sound (ρc).

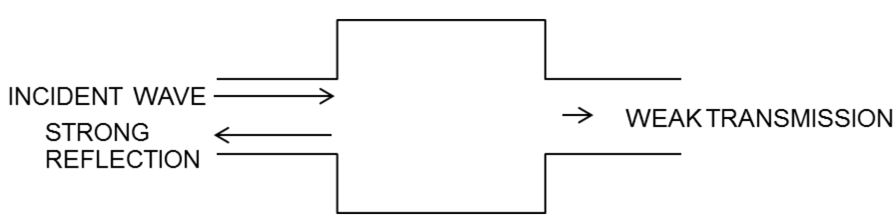

Figure 1: Reactive silencer.

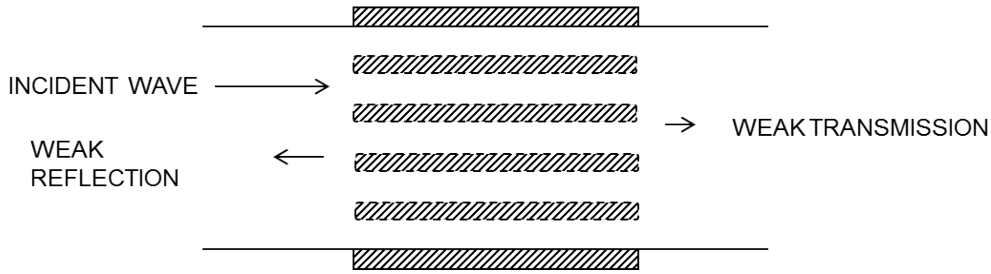

Figure 2: Absorptive silencer.

3 MODELLING METHODS

Both traditional and more advanced numerical methods have been applied to the case studies illustrated in the paper. Apex[1] is a one dimensional analytical modelling software, developed over many decades at ISVR, University of Southampton, which includes empirical corrections to account for higher order duct modes in the chambers and discontinuity effects. It only requires geometrical and acoustic flow properties as input and provides sound attenuation and far field pressure transfer function as result. It is computationally very efficient, the running time is on the order of few minutes, but it is only suitable to standard chambers connected through pipes with uniform flow at low frequency.

Actran[2] is an acoustic FEM (finite element model) tool, which takes into account the complete 3D geometry. It can model unconventional chamber shapes, higher duct mode interactions and non-uniform flow effects. As inputs, Actran requires the discretized volume mesh plus acoustic and mean flow parameters, and, as results, it computes the acoustic pressure and power for all incident, transmitted and reflected waves both in the near and far field. Therefore, it is much more versatile than Apex, but computationally more expensive. However, at low frequency where Apex is applicable, the running time is still relatively low, generally less than one hour.

Computational fluid dynamics (CFD) is also very useful in designing silencers. It is applied to assess the backpressure and the internal flow quality and provides the non-uniform mean flow necessary to the acoustic FEM when high speed flow affects the acoustic performance. However, the 3D volume needs to be discretized in a generally finer mesh than necessary for the acoustics and computational convergence can be an issue.

4 CASE STUDIES

4.1 Design of absorptive silencers for the Anecom test facility

The ANECOM test facility is a specialist test rig for measuring the aerodynamic performance and noise of aeroengine fans (Figure 3). Measurements of noise made in the bypass duct are affected by noise generated by the flow control throttle and also by acoustic reflections from the throttle. As part of a re-design to increase flow capacity, Actran was used to design silencers[3] that would reduce the level of control throttle noise propagating upstream in the bypass duct by 20dB and would also reduce the in-duct reflection coefficient for fan noise propagating downstream to below -8dB. Those specifications had to be achieved for most throttle settings and mass flow rates in a broad frequency range of interest.

Figure 3: Anecom test facility.

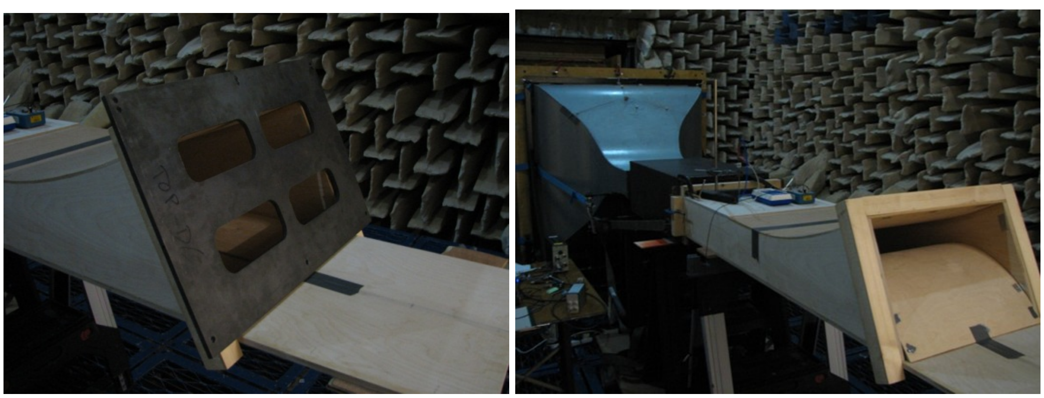

Figure 4: Throttle design, from the old slot (left) to the new flap concept (right).

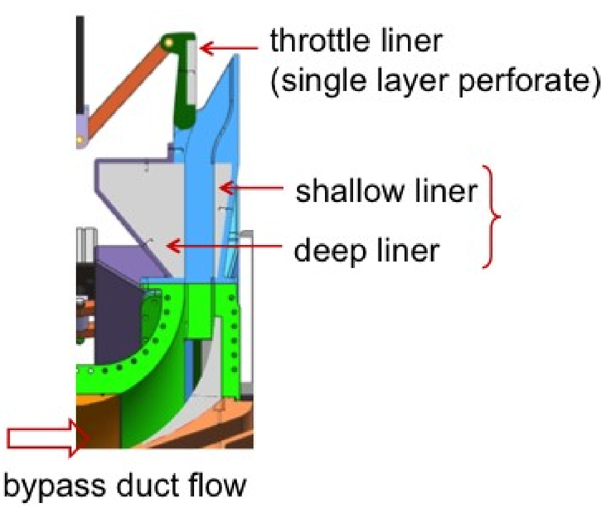

Figure 5: Acoustic liners in the duct upstream of the throttle and on the throttle.

Firstly, a new throttle design was introduced, replacing the slot concept with a flap throttle (Figure 4), which had the advantage of decreasing the pressure loss and aeroacoustic noise, allowing both an increase in mass flow rate and a reduction of noise at source.

Secondly, acoustic liners were included in the duct, both upstream of the throttle and on the throttle itself, as shown in Figure 5. Actran was used to explore the possibility of using single/double layer perforates or bulk absorbing material for the shallow and deep liners, which have various pros and cons: Perforate liners are more expensive to build and replace, but not liable to suffer from contamination; bulk absorbing liners are cheaper, but more easily contaminated.

Figure 6 shows the Actran model used in the analysis. A plane of symmetry, and incident and transmitted duct modes were defined as shown in the picture. The reflection coefficient was defined as the ratio of the incident power and the power reflected back into the bypass duct; the transmission coefficient was the ratio of the incident power over the throttle duct transmitted power. Varying the liner parameters had little effect on the reflection coefficient, while high variability was found on the transmission coefficient.

The transmission coefficient contour plots used to optimize the porous and perforate liners are shown in Figure 7 and Figure 8 respectively. Porous liners perform better with a low facing sheet resistance and high flow resistivity for the bulk material. Perforate liners perform better for low resistance and reactance at low frequency, but shifting to R = 1ρc and X = -2ρc at higher frequency.

Based on this analysis one porous and two perforate liner candidates were considered, as summarised in Table 1. As already noted, Figure 9 confirms that the reflection coefficient is not controlled by the throttle liners. In most of the frequency range, the target is met no matter which throttle liner is used, because the duct bend and the bypass liners attenuate the sound effectively. Different conclusions can be drawn for the transmission coefficient, as shown in Figure 10. Here results are presented by marking the 20dB attenuation target and taking into account the noise reduction at source obtained with the new flap throttle. The three liners perform differently varying the frequency range. The porous liner attenuates better at mid-frequencies, whilst the perforate liners work better at low frequency, ‘perforate 1’ works especially well at higher frequency and, over 3000Hz all the liners are just on the target. In conclusion, the combined effects of modifying the throttle design and optimising the throttle liners achieved the specified acoustic target.

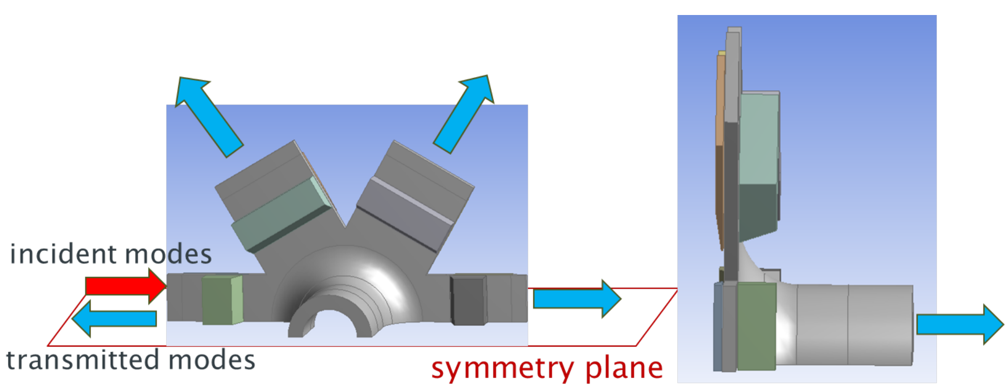

Figure 6: Actran model including a symmetry plane, incident wave in red and transmitted wave in blue.

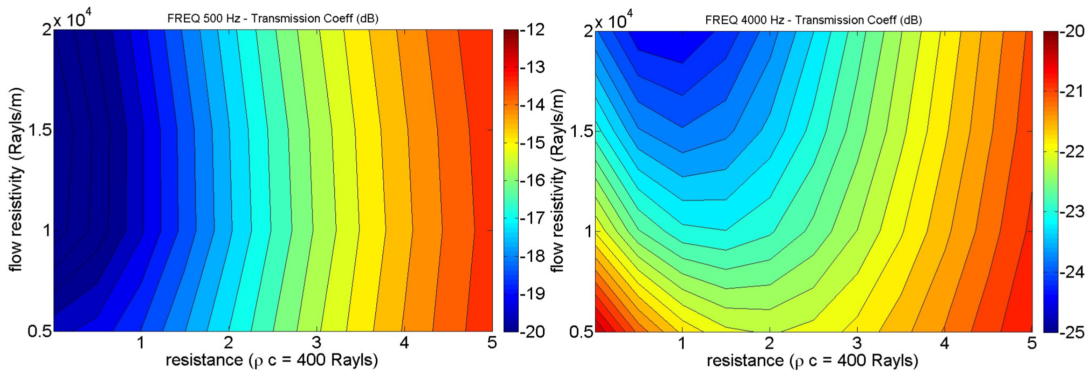

Figure 7: Porous liner optimisation. Transmission coefficient (dB) at low (left) and high (right) frequency by varying the material flow resistivity and facing sheet resistance.

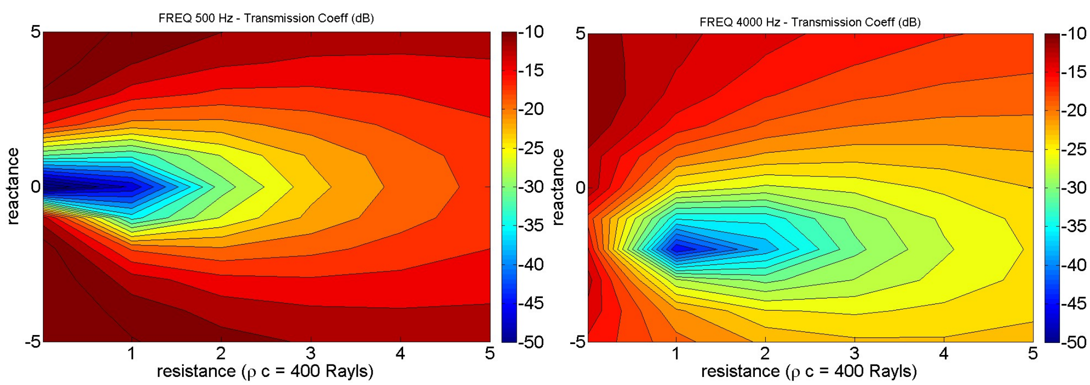

Figure 8: Perforate liner optimisation. Transmission coefficient (dB) at low (left) and high (right) frequency by varying the liner resistance and reactance.

Table 1: Optimised liner candidate specifications.

Liner type	**Specification**
porous	high flow resistivity low resistance facing sheet
deep perforate	low resistance facing sheet 2 cavity depth candidates
shallow perforate	high resistance facing sheet 2 cavity depth candidates

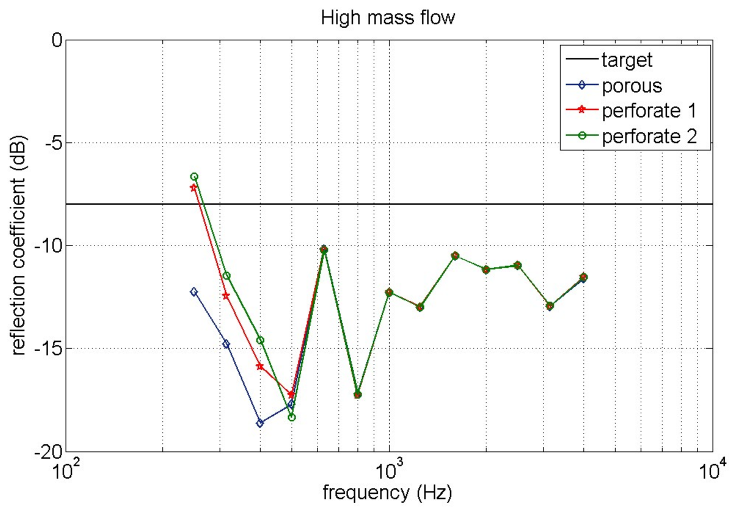

Figure 9: Reflection coefficient (dB) for the different liner candidates.

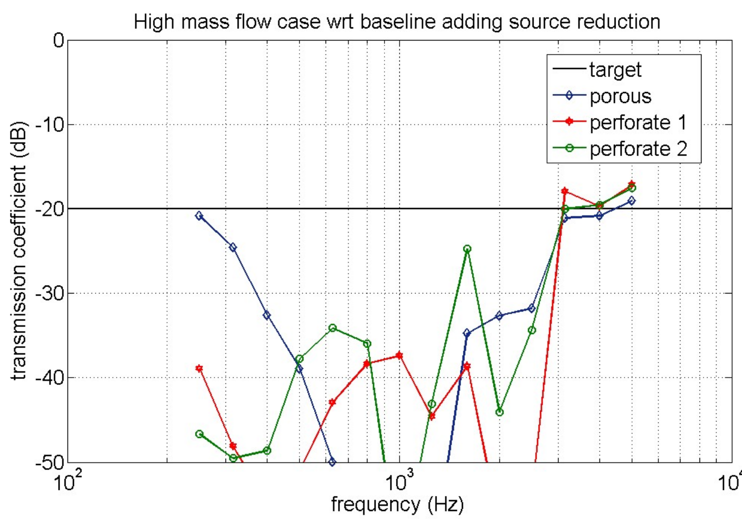

Figure 10: Transmission coefficient (dB) for the different liner candidates when adding noise reduction at source.

4.2 Validation of FEM on a simple reactive silencer

In this section a test case of a reactive silencer is presented to validate Actran against Apex. In the Actran model only the expansion chambers are discretised and solved numerically, while the linking pipes between chambers are modelled analytically using the Transfer Matrix Method (TMM); this has the benefit of significantly reducing the volume to be discretised.

A simple axisymmetric expansion chamber linked to a tail pipe and radiating into the far field is considered, as shown in Figure 11. This has been modelled both in Actran and in Apex to validate the prediction method used to assess the sound attenuation of the system: the ratio in dB between the incident pressure at the inlet and the transmitted pressure at the outlet. System attenuation is one way of characterising the performance; other performance parameters that can be predicted include insertion loss and transmission loss, as discussed below. The comparison between Actran and Apex results is shown in Figure 12. The agreement is good, but deteriorates at high frequency, partly because Apex has a number of analytical approximations that reduces its accuracy at higher frequencies.

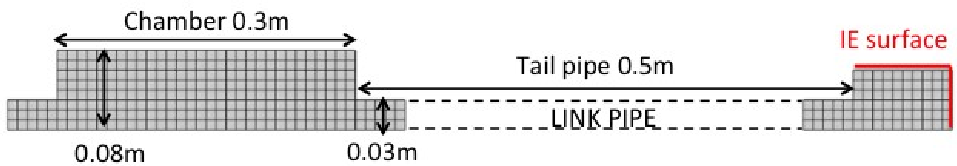

Figure 11: Simple axisymmetric expansion chamber with a link pipe radiating to the far field by using an infinite element (IE) surface. Wave propagating from left to right.

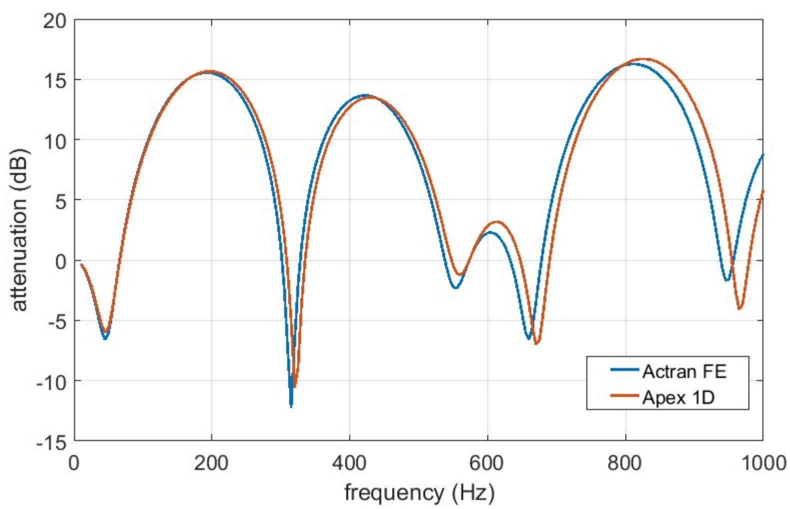

Figure 12: Comparison of sound attenuation calculated by Actran and Apex.

4.3 Application of FEM to complex reactive silencer geometries

Two designs of a reactive silencer developed for a marine application have been analysed by comparing various sound attenuation parameters using Actran. The first silencer, named here as 'design 3', is a combination of two expansion chambers and a Helmholtz resonator, the second one named as 'design 5' is composed by three expansion chambers, with reversed flow. This is considered to enhance the acoustic performance, but could strongly increase the backpressure. Therefore, CFD was also employed to assess the pressure loss and compare the flow characteristic of the two designs.

Three different attenuation parameters were defined and compared in Figure 13, considering 'design 3' as reference:

- Far field Transmission Loss (ff_TL) = ratio in dB of the incident acoustic power at the inlet over the radiated power in the far field;

- Far field Pressure TL (ff_PTL) = ratio in dB of the pressure amplitude (sum of incident and reflected) at the inlet over the transmitted pressure amplitude in the far field;

- TL at the outlet (notail_TL) = ratio in dB of the incident acoustic power at the inlet over the transmitted power at the outlet, but considering the tail pipe as infinite, thus with no reflection from the outlet.

The ff_PTL is generally used to assess the silencer performance experimentally, while the notail_TL is better used numerically, because it is not necessary to discretise the far field domain. Figure 13 shows that the ff_TL and the notail_TL are equivalent, having the same attenuation features, while the ff PTL has more dips, due to the effect of the reflected pressure component in the inlet pipe which creates standing waves. However, the main features are well characterized by all the attenuation parameters.

Figure 14, Figure 15 and Figure 16 show the three attenuation parameters compared for the two silencer designs. From all the pictures it is clear that 'design 5' performs generally better in most of the frequency range. Only in the 200Hz region 'design 3' is more effective. However, when CFD was used to evaluate the effect of the reversed flow on the pressure loss, it occurred that the 'design 5' backpressure was about 50% higher than 'design 3' one. This demonstrated how assessing the flow quality is crucial during the design process and needs to be taken fully into account when comparing different designs.

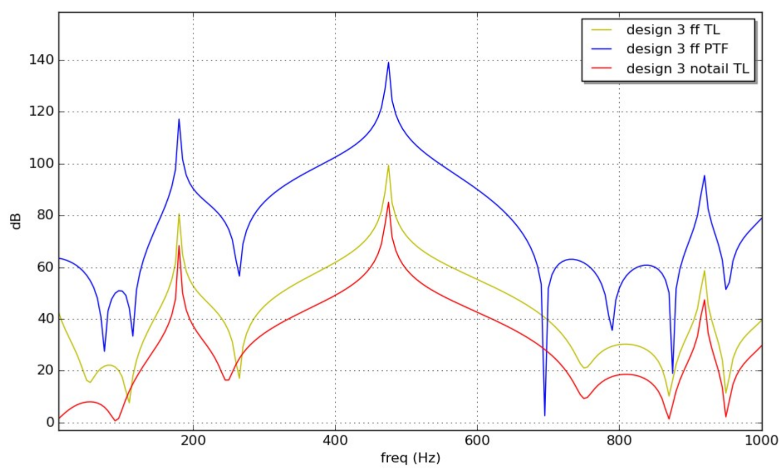

Figure 13: Comparison of different sound attenuation parameters on 'design 3' silencer: far field Transmission Loss (ff TL), far field Pressure Transmission Function (ff PTF) and no-tail pipe TL (notail TL).

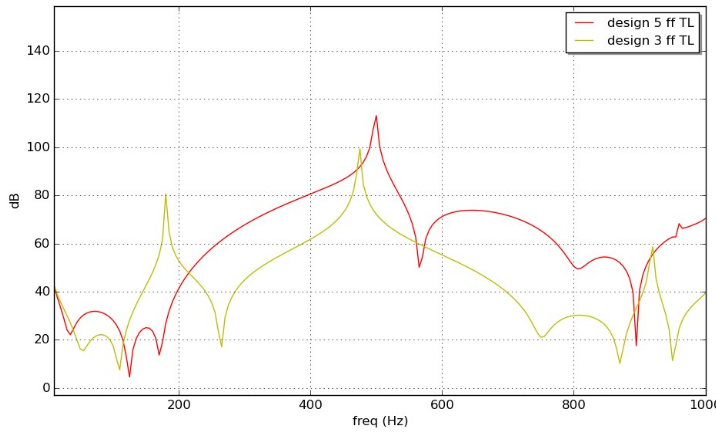

Figure 14: Comparison of far field TL of 'design 3' and 'design 5' silencers.

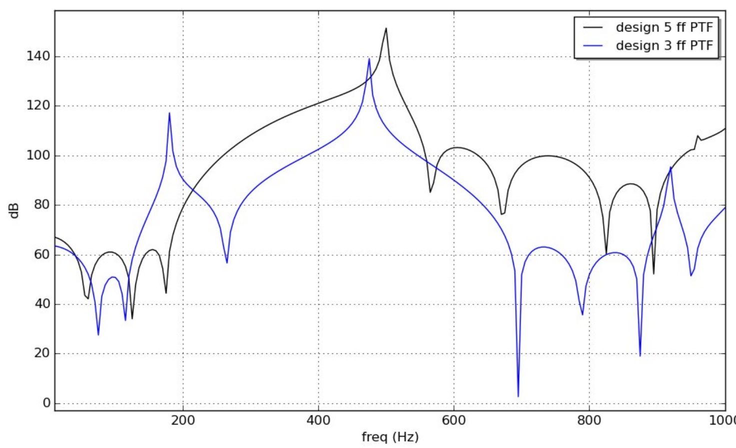

Figure 15: Comparison of far field PTL.

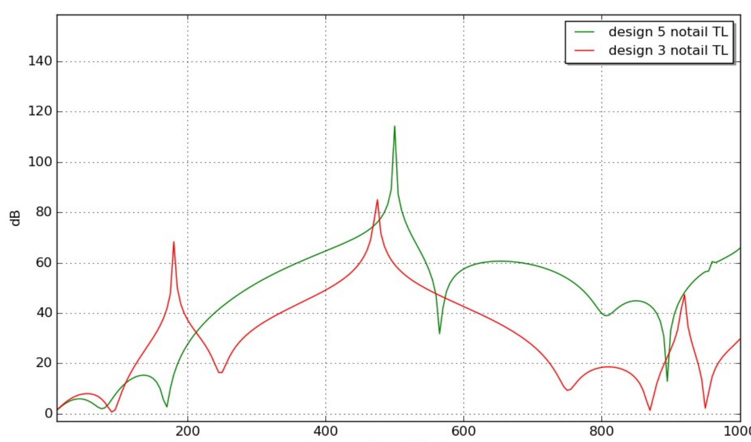

Figure 16: Comparison of TL with no tail pipe.

5 CONCLUSIONS

In this paper traditional and numerical methods have been applied to the design of different types of silencers. The three case studies of absorptive and reactive silencers have shown that advanced numerical methods have excellent potential for design optimisation. Various modelling methods were applied in exploring the design optimization parameters of liners and silencers, the flexibility of defining the sound attenuation characteristics in different ways and the usefulness of being able to analyse isolated components if necessary. Furthermore, only these modern numerical methods can model complex shapes and take into account the effect of non-uniform flows, including backpressure as a design constraint.

6 REFERENCES

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3. E. Quaranta and M.G. Smith, "Acoustic optimisation of a fan test rig," in *FFT acoustic simulation conference*, Bruxelles,, (2014).