The effect of high temperatures and grazing flow on the acoustic properties of liners

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Summary
Acoustic liners are used to reduce fan noise in aircraft engine intakes but also in hot stream parts of the engine. To gain confidence in liner impedance models which are used for design it is important to make experimental tests under realistic conditions as possible. This paper present results of hot stream impedance eduction tests for single degree of freedom Helmholtz resonator liners with different configurations. These types of liners consist of a perforate top sheet backed by a honeycomb cavity to give a locally reacting wall treatment which can be characterized by an acoustic impedance. In the present case a number of different perforate sheet geometries were tested under varying grazing flow and temperature conditions. In some cases the liner test samples also included a thin layer of metallic foam. These types of liners are used for aircraft engine applications but are also of interest for IC-engine applications. It could be argued that the main effect of high temperatures is a change of medium properties such as: density, viscosity and speed of sound. If this is true the high temperature impedance could be predicted by scaling from the result at cold conditions. This is investigated in the paper by comparing measured results from liner impedance models available in the literature.

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1. Introduction

Acoustic liners are used in the intake of aircraft engines to reduce fan noise. There is now an interest in putting sound absorbing liners also in other parts of the engine, for instance under high temperature conditions. A large effort has during the last 20 to 30 years been made to develop methods for extracting the relevant acoustic liner properties, the acoustic impedance, under grazing flow conditions [1-11]. A limited number of studies have been devoted to study the effect of high temperatures [12-17]. In [13,15] impedance tube measurements on liners under hot conditions were studied. A hot stream liner test facility at NLR in the Netherlands was described in [12] and used for comparing different types of liners in [14].

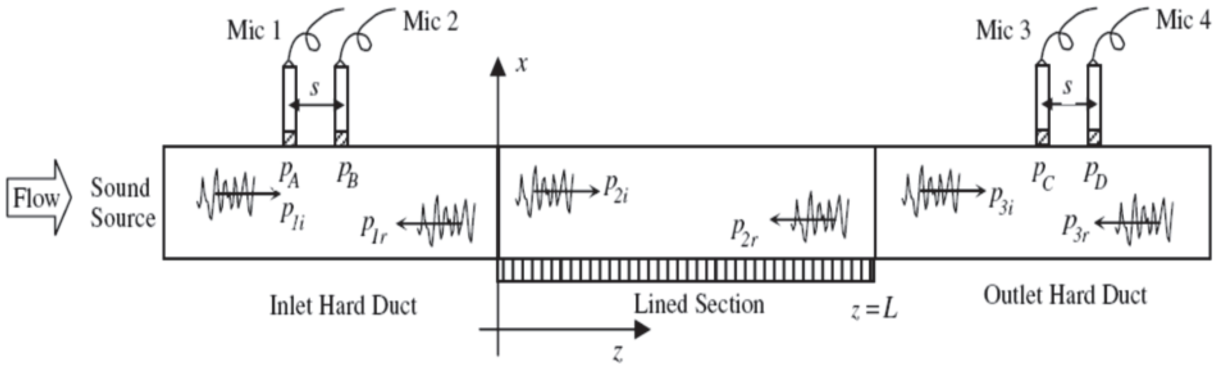


Figure 1. Test setup [27].

The results reported in this paper are part of the EU funded Clean Sky Project HOSTEL (Integration of a HOt STrEam Liner into the Turbine Exit Casing (TEC) within theme JTI-CS-2011-3-SAGE-04-017, Grant Agreement 308265). The effect on the result of test rig geometry and mean flow profile was discussed in [17], together with the effect of high temperatures. A limited comparison with a liner impedance model was also made. In the present paper further comparisons with models from the literature [18-20] are made in order to further investigate if the effect of high temperature flow on the liner impedance data can be predicted and scaled using a change in media properties: density, viscosity and speed of sound.

2. Impedance eduction method

A number of different impedance eduction methods were discussed in [6]. The results presented here were obtained using the Convected Helmholtz Euation (CHE) is used with plug flow and the Ingard-Myers boundary condition. Details of this method has been published elsewhere [7,8,17]. It is assumed that plane waves are incident on the lined section from the hard walled ducts, see Fig. 1. The propagation in the lined section is solved for analytically assuming uniform flow and an impedance boundary condition on one side of the rectangular test section duct. Mode matching is used to calculate the transmission between the lined and the hard walled duct sections. The impedance is obtained by minimizing the difference between the measured and calculated pressures at the microphone positions in the hard walled ducts on both sides of the lined section.

3. Liner impedance models

In [7,18] a semi-empirical model for perforate resistance and reactance was presented. It summarizes previously published models and adds a few improvements to the resistance and reactance end corrections and the resistive and reactive terms associated with nonlinearities and grazing flow.

$$r = \mathrm{Re}\left[\frac{jk}{\sigma C_D}\left(\frac{t}{F(\mu')} + \frac{\delta_{re}}{F(\mu)} f_{int}\right)\right] + \frac{1}{\sigma}\left[1 - \frac{2J_1(kd)}{kd}\right] + R_M \frac{M}{\sigma}, \qquad (1)$$

$$x = Im\left[\frac{jk}{\sigma C_D}\left(\frac{t}{F(\mu')} + \frac{d}{2F(\mu)} f_{int}\right)\right] - 0.3\frac{M}{\sigma}, \qquad (2)$$

where r is the normalized resistance and x is the normalized reactance, k is the wave number, σ is the perforation ratio (percentage open area), C_D is the discharge coefficient, t is the plate thickness, μ

is the adiabatic dynamic viscosity, $\mu' = 2.179\mu$ is the dynamic viscosity close to a conducting wall, $\nu = \mu/\rho$ is the kinematic viscosity, J is the Bessel function, d is the hole diameter, c is the speed of sound, v_n is the peak value of the acoustic particle velocity incident on the sample R_M is an empirically determined constant and M is the grazing flow Mach number. The empirical constant R_M which is part of the term which accounts for the effect of mean flow Mach number on the resistasnce was in[28] determined to 0.5 while in[29] the value 0.15 was obtained. The rest of the parameters are defined as:

$$K = -\sqrt{\frac{j\omega}{\nu}}, \tag{3}$$

$$F(\mu) = 1 - \frac{4\cdot J_1(Kd/_2)}{Kd\cdot J_0(Kd/_2)}, \tag{4}$$

$$\delta_{re} = 0.2d + 200d^2 + 1600d^3, \tag{5}$$

$$F_{int} = 1 - 1.47\sqrt{\sigma} = +0.47\sqrt{\sigma^3}, \tag{6}$$

The effect of temperature is included in this model through the density, speed of sound and viscosity. The effect of mean flow is, as mentioned above, included as terms proportional to the mean Mach number.

For comparison another model suggested by Atalla and Sgard [20] based on a Biot type of theory for the perforate, has also been used. This model gives the no flow perforate impedance as

$$Z_P = \left(\frac{4t}{d} + 8\frac{\sigma}{d}\right)\frac{R_s}{\sigma} + \frac{1}{\sigma}(2\varepsilon_e + t)j\omega\rho_0, \tag{7}$$

Where R_s is the surface resistance defined as

$$R_s = \frac{1}{2}\sqrt{2\eta\omega\varrho_0}, \tag{8}$$

and the hole interaction factor is given by

$$\varepsilon_e = \frac{4d}{3\pi}\left(1 - 1.14\sqrt{\sigma}\right). \tag{9}$$

The temperature again enters through the resistance, speed of sound and viscosity. Mean flow effects are taken into account when using this model in the same way as in equation 1-2 since the Atalla and Sgard model does not include the effect of mean flow.

The effect of temperature is included in the density, speed of sound and viscosity through:

$$\rho = {}^{\rho_0}/_{T}, \tag{10}$$

$$c = c_0\sqrt{{}^{T}/_{T_0}}, \tag{11}$$

$$\mu = \mu_0\frac{(T_0+C)}{(T+C)}\left(\frac{T}{T_0}\right)^{3/2}, \tag{12}$$

Where T_0 = 291.15 K, c_0 = 343.4 m/s, μ_0 = 1.827e-5 Pas and Sutherlands constant C is 120 K.

4. Test setups

Three different test configurations have been used for obtaining liner impedance. A normal incidence impedance tube was used to get a room temperature no flow reference for the liner impedance. High temperature measurements with low flow speeds were made using hot air blowers. The test setups are described in [17]. High flow speed measurements at moderate temperatures were made using a compressed air facility in the CICERO lab at KTH.

In order to characterize the flow field, a Pitot tube and temperature sensor section was included upstream of the sample. Both the Pitot tube and temperature sensor were traversed over the height of the duct. This section was removed during the acoustic tests i.e. the temperature and the flow was measured at the position of sample holder in acoustic testing. In addition, a temperature sensor was traversed inside one of the liner sample cavities.

The starting point for the liner sample development was the so-called SAAB hybrid liner[24] studied in the EU project SILENCE(R). This liner had a perforate top sheet with 20% open area, thickness 0.65 mm, hole diameter 0.75 mm in combination with a metallic foam and a cavity with depth of 19 mm. The perforate sheet and honeycomb cavities were made from Inconel 625 and the metallic foam was Nickel based. In the present study a modular liner test sample, has been utilized consisting of a solid back plate, a cavity section with 4x8 rectangular cross section cavities with the inner dimensions of 6.9x6.9 mm, metallic foam layer and perforated top sheet. Measurements were made for a large number of test configurations. In the present paper mainly results obtained using a perforate with 16.3 % open area, with or without a metallic a foam layer with surface density of 600 g/m^2 and with the 19 mm cavity were included.

5. Results and discussion

5.1 Experimental liner impedance results

When conducting impedance eduction using the Convected Helmholtz equation mode matching (CHE) method one need to decide how many modes to include in the mode matching. By conducting investigations using 1, 2 and 5 modes for different test cases it was concluded [17] that 5 modes was sufficient to get a converged result. All the remaining impedance measurement results have been obtained using 5 modes for the mode matching.

Figure 2 shows a comparison of results obtained for the high flow speed test cases. It can be seen that an increase in flow speed increases the resistance and decreases the reactance as expected from the models discussed in section 3. A moderate increase in temperature does not change the resulting impedance when plotted against the Helmholtz number. In the model according equation 1 it is expected that for a Mach number equal to 0.25 the normalized resistance should increase by ~ 0.77 if R_M = 0.5 while the normalized reactance should decrease by a factor ~ 0.46. In the model from [19] R_M = 0.15, which would give an increase in normalized resistance of 0.23 for M = 0.25. This is in better agreement with the high flow speed results presented in Figure 2.

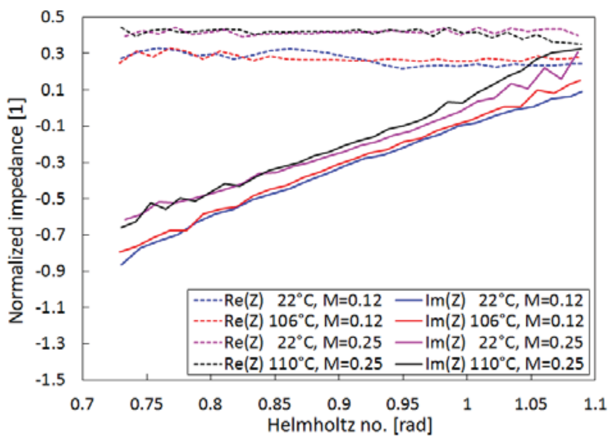


Figure 2. Comparison of measured impedances for high flow speed test cases.

5.2 Comparison with liner impedance models

To gain confidence in the impedance models comparisons were first made between the impedance tube results and corresponding models according to section 3. Most input parameters to the models are given by the liner geometry and temperature measurements. For the cases with mean flow the mean flow Mach number is also needed. For the model according to [7,18] the discharge coefficient (C_D) is also required. Here we have used the empirical discharge coefficients from [7] which gives the value 0.84 for the studied sample.

Figures 3 shows an example of the results obtained. It can be seen that the agreement is good and that the model according to [18,19] gives a slightly better agreement with the experimental results.

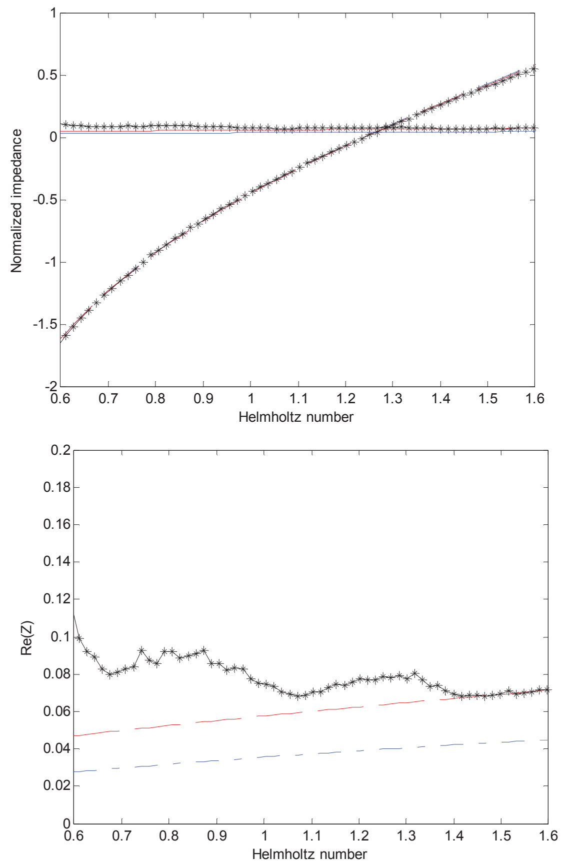
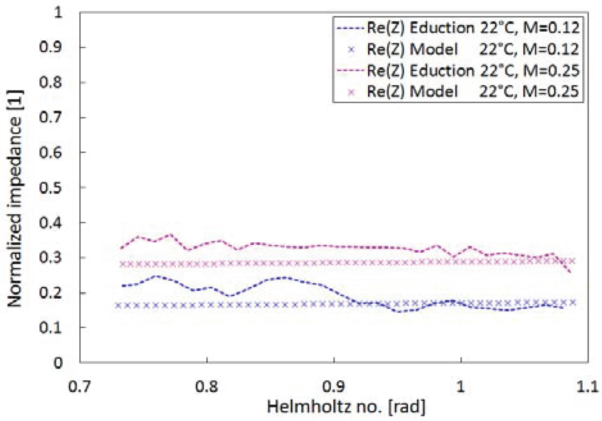
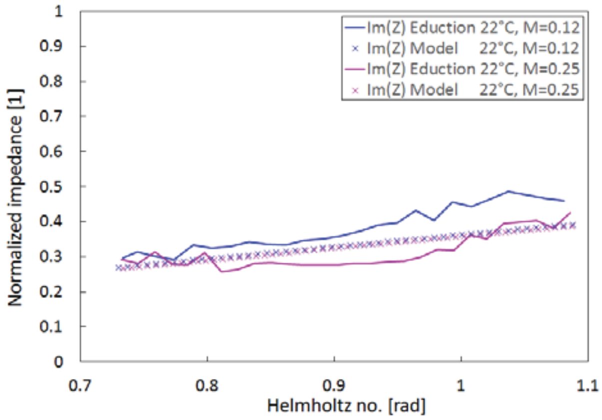


Figure 3. Comparison of measured and simulated impedance tube result for perforate with parameters: T = 297.9 K, s = 0.159 and CD = 0.84, black – experimental result, red – Elnady model[28], blue – Atalla and Sgard model[30], a) Real and imaginary parts of impedance.. b) Real part of impedance.

Figure 4 shows a comparison between measured and simulated impedance for the high flow speed test cases. The simulations are based on the model presented in section 3 using R_M = 0.15 from [19] for the dependence of resistance on flow Mach number. It can be seen that there is a reasonably good agreement between the measured and simulated impedance.



a)



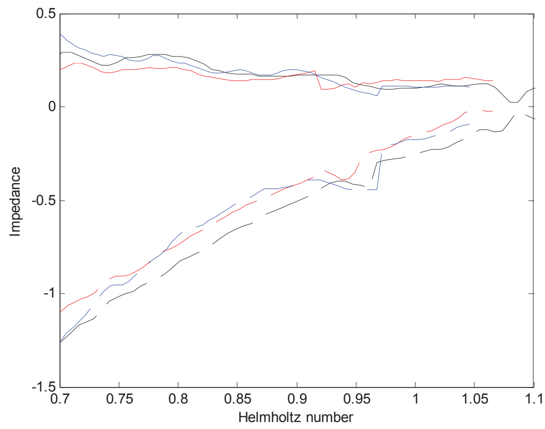
b)

Figure 4. Comparison of measured and simulated impedances for the high flow speed test cases for a liner sample without foam. a) Real part of normalized impedance, b) Imaginary part of normalized impedance.

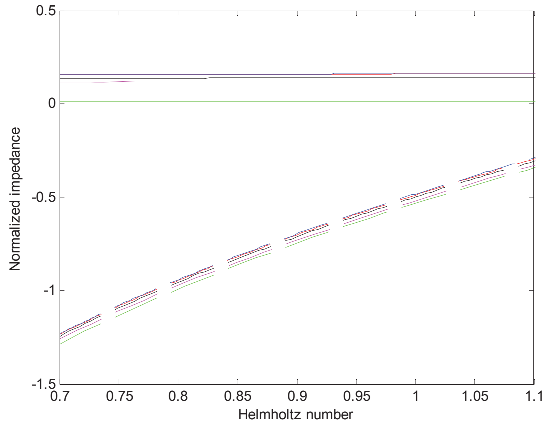
Figure 5 shows the effect temperature variation for the low flow speed high temperature test cases. It can be seen that the general trends are captured quite well even though the scatter is a bit larger in the experimental results. In the simulation room temperature results with and without flow has been added. It should be pointed out that for these low flow speeds cases a factor $R_M = 0.5$ gives the best fit for the resistance. This means that a different factor to account for the effect of flow on resistance has been used in the results presented in Figure 4.

1. Conclusions

A limited number of studies regarding effects of high temperature flows on acoustic liner properties have been reported in the literature. The present study is motivated by the need to understand how to accurately design optimized liners for high temperature flow applications. If all the effects of high temperatures can be modelled as a change in fluid media properties (speed of sound, density and viscosity) then development and testing could be made under cold flow conditions and scaled to high temperatures.



a)



b)

Figure 5. Normalized liner impedance for the high temperature low flow speed test cases, black – T = 413 K, M = 0.043, red – T = 538 K, M = 0.046, blue – T = 565 K, M = 0.042, magenta - T = 297 K, M = 0.045, green – T = 297 K, M = 0, solid line – real part, dashed line – imaginary part. a) Experimental result, b) simulation.

An experimental test campaign has been performed [17] where a fairly large number of different single degree of freedom Helmholtz resonator liners, sometimes including a sheet of metallic foam behind the perforate plate, has been tested in three different test rigs: an impedance tube, a high temperature low flow speed test rig and a high flow speed test rig.
It was found that there is a good agreement between the results of the impedance tube tests and the grazing flow configuration test rig results for no flow room temperature conditions.
The effect of high temperatures and mean flow on the liner impedance data was studied. It was found

that plotting impedance data against Helmholtz number gave a reasonable collapse of results with the same flow speed but different temperature. Comparisons have also been made using models from the literature [7,18-20]. It seems that the effect of high temperature can be fairly well predicted and scaled using a change in media properties: density, viscosity and speed of sound and that the main difficulty is to accurately determine the effect of mean flow. The models used here have terms proportional to the mean Mach number to account for the effect of mean flow on both resistance and reactance. For the reactance a term $-0.3M/\sigma$ seems to give a reasonable agreement between model and experimental results. For the resistance a term $R_M M/\sigma$ was used where $R_M = 0.15$ [19] gave the best results for the high flow speed cases ($M = 0.12$ and 0.24) while $R_M = 0.5$[28] gave a better result for the low speed high temperature test cases ($M = 0.045$). This indicates that a term simply proportional to flow Mach number is an over-simplification.

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