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Low frequency liners for turbofan engines

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ABSTRACT

Reducing aircraft noise is critical to the growth of air transport and for quality of people's life. The aircraft noise is composed of contributions from various source mechanisms and fan noise is one of the dominant components at take-off and landing for aircraft with modern high bypass ratio turbofan engines. Fan noise is generated at the fan, propagates through engine intake and bypass duct and is radiated to the outside. Acoustic liners are applied on the internal walls to attenuate the fan noise while it propagates through the engine ducts. Typical engine duct liners are either so-called single degree of freedom (SDOF) or double degree of freedom (DDOF) liners. SDOF liners consists of a porous facing sheet backed by a single layer of cellular separator such as honeycomb cells with solid backing plate, and in case of DDOF liners two cellular layers are separated by porous septum sheet. The acoustic performance of such liners is strongly dependent on the depth of the cell(s). Generally these liners are selected to be most effective to reduce community noise measured with EPNL(dB) and typical liner cell depth is around 1 to 2 inches. In order to increase the attenuation by the liners at lower frequencies the cell depth must be made larger, which is often prohibited by the mechanical design constraints. One remedy can be the acoustic liners having L-shaped geometry so that it can fit in a shallower space. In this study a potential of folded cavity liners is investigated. Such liners have the potential to behave like a mixture of deep and shallow liners. They have more complex frequency characteristics due to the fold compared to conventional liners and can be used to reduce noise over wider frequency range. Finite element models are used to assess the acoustic performance of liners.

INTRODUCTION

Reducing aircraft noise is critical to the growth of air transport and for quality of people's life. The aircraft noise is composed of contributions from various source mechanisms and fan noise is one of the dominant components at take-off and landing for aircraft with modern high bypass ratio turbofan engines.

Fig. 1 shows the noise sources of modern High Bypass Ratio (HBR) turbofan engines1. Fan noise is major noise source at the approach and take-off conditions. It is generated at the fan, propagates to the forward arc through the intake and to the rear arc through the bypass duct, and is then radiated to the outside.

The aircraft noise is regulated with EPNL (Effective Perceived Noise Level) measured for three certification conditions, namely, approach, cutback and sideline. The typical proportions of contributions from different noise sources in these conditions are illustrated in Fig. 2. Fan noise is particularly dominant component at approach condition, but is still quite important also in other conditions.

One of, and most typical of acoustic treatments for reducing fan noise radiated to the far field is using acoustic liners. Liners are applied on the internal walls of engine intakes and bypass ducts, in order to attenuate the fan noise while it propagates through the ducts before it is radiated to the exterior. Typical liners used for this purpose in turbofan engines are either so-called single degree of freedom (SDOF) or double degree of freedom (DDOF) liners. The acoustic performance of these liners is strongly dependent on the cell depth. Generally the liners are selected to be most effective to reduce community noise frequencies and typical liner cell depth is around 1 to 2 inches.

One remedy can be having folded SDOF liners which has a large total length but is bent at small distance from the top surface so that it can fit in a shallow space. Such liners have the potential to behave like a mixture of deep and shallow liners.

In this paper the acoustic behaviour of folded liners is studied. They have more complex frequency characteristics due to the fold compared to conventional liners and can be used to reduce noise over wider frequency range. Finite element models are used to assess the acoustic performance of liners. Parametric studies are performed and the noise reduction capability when installed in an engine intake is demonstrated.

CONVENTIONAL ACOUSTIC LINERS IN AIRCRAFT ENGINE DUCTS

A typical construction of SDOF liners is shown in Fig. 3. The liner consists of a porous facing sheet backed by a single layer of cellular separator such as honeycomb cells with solid backing plate. In case of DDOF liners two cellular layers are separated by porous septum sheet. The acoustic performance of these liners, particularly SDOF liners, is strongly dependent on the cell depth. The expression of acoustic impedance of a SDOF liner with the facing sheet resistance

$$\frac{Z_{fs}}{\rho c} = R_{fs} + i\chi_{fs} \qquad (1)$$

where ρ, c are the fluid density and speed of sound in the medium, and cell depth d is given by

$$\frac{Z}{\rho c} = R + i\chi = R_{fs} + i\{\chi_{fs} - cot(kd)\} \qquad (2)$$

where $k = 2\pi f$ is the wavenumber of acoustic wave at frequency f Hz. In the current study, non-dimensional facing sheet

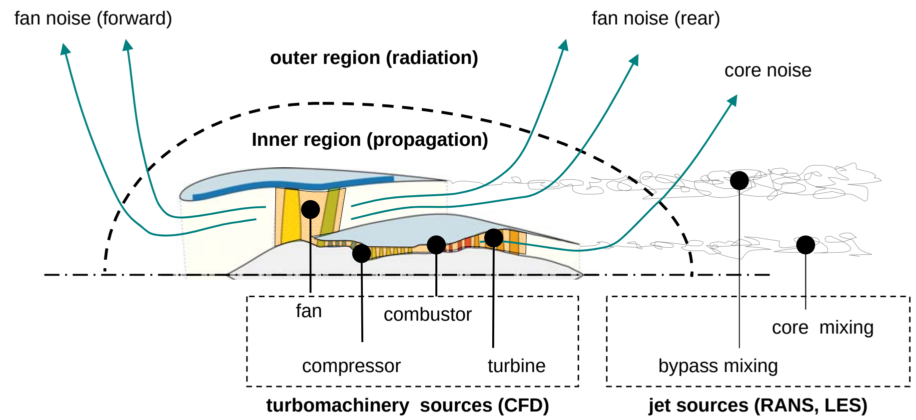

Figure 1: Noise sources and transmission paths in a turbofan engine

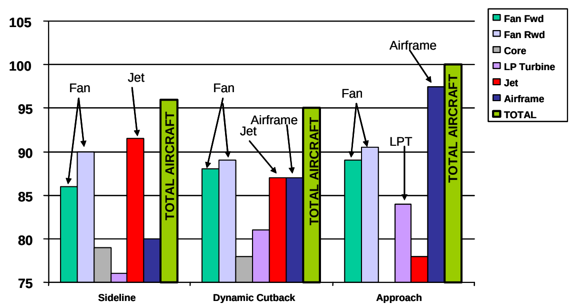

Figure 2: Contributions from different noise sources

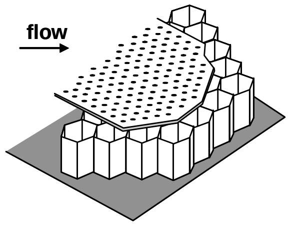

Figure 3: Typical construction of SDOF acoustic liner

resistance R_{fs} is fixed to 0.5 and the non-dimensional facing sheet reactance χ_{fs} is kl where χ_{fs} is given by kl. The mass inertance l is fixed to the value of 0.009.

Figs. 4 and 5 show examples of normal incidence acoustic impedance and absorption coefficient, respectively, of SDOF liners with different cell depth d.

Fig. 5 shows that the first maximum of the absorption coefficient by the SDOF liners occurs at 1440Hz, 530Hz, 280Hz and 170Hz for the cell depth 5cm, 15cm, 30cm and 50cm, respectively. These first peaks naturally occur when the cell depth is close to a quarter a wavelength, and the pattern is repeated when the cell depth satisfy roughly $d = \lambda(2n-1)/4$ where λ is the wavelength and n is positive integers. More precisely, the peaks occur when the reactance becomes close to zero which is determined by the wavelength and cell depth as well as the

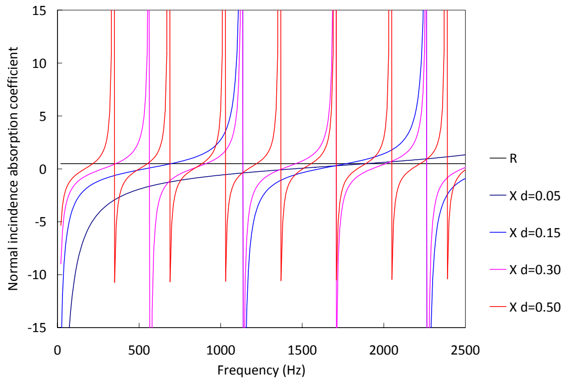

Figure 4: Normal incidence acoustic impedance of SDOF acoustic liners with different cell depth d

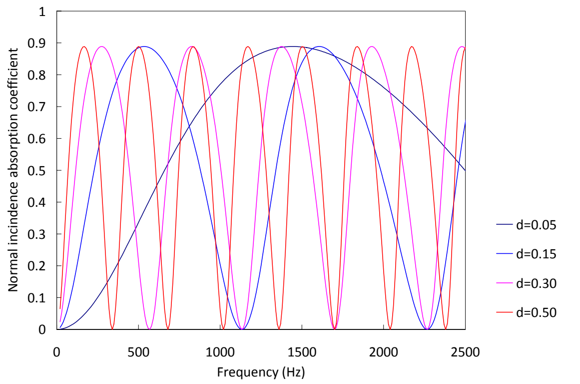

Figure 5: Normal incidence absorption coefficient of SDOF acoustic liners with different cell depth d

mass inertance of the facing sheet. It can be confirmed from Fig. 4.

FOLDED LINERS

For the turbofan engine applications, generally the liners are selected to be most effective to reduce community noise frequencies and the typical liner cell depth is around 1 to 2 inches. In order to increase the attenuation by the liners at low frequency range, the cell depth needs be made greater. But it is

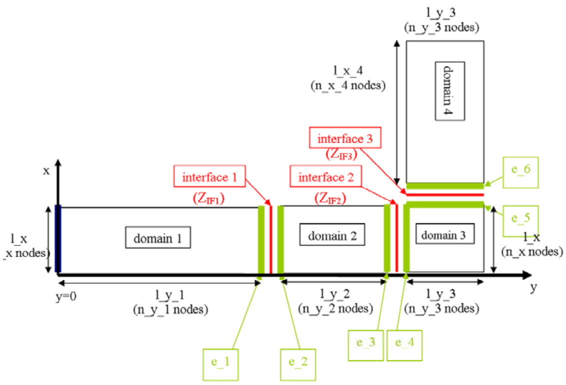

Figure 6: Finite element model for folded liner analysis

often prohibited by the mechanical design constraints.

One remedy can be folding the liner so that total depth - the length of the path to the bottom of the cell - is much longer than the conventional liners while the vertical space required to install it is small. Such a liner can have the potential to behave like a mixture of deep and shallow liners.

Numerical model

In order to calculate the acoustic impedance of folded liners, a Matlab script which produces a finite element model for a given set of parameters has been developed. The finite element analysis domain consists of multiple sub-domains coupled by a transfer matrix which relates the acoustic pressure and particle velocity on both sides of the interface between two neighboring domains.

The four-domain model shown in Fig. 6 includes domain 1 which models an impedance tube in which a plane wave propagates from the left end (source plane) towards the right end at which a liner cell is attached. The domains 2 to 4 are to form a folded liner. The interface between domains 1 and 2 is the surface of the liner and facing sheet impedance is set for this interface. If the interface between domains 3 and 4 is set to be rigid (with very large impedance) the wave does not propagate into domain 4 and a straight liner can be modelled in this way.

Finite element analysis for the acoustic wave propagation was performed by using a commercial CAA code ACTRAN/TM [4] developed by Free Field Technologies SA. ACTRAN/TM is an FE/IE programme which solves the linearised Euler equations for aeroacoustic propagation problems. The FE/IE model of the type proposed and developed by Astley [1] and Eversman [2] is implemented in ACTRAN/TM.

NUMERICAL EXAMPLE

Depth parameters

The ACTRAN FE models have been created for different liner geometries to investigate the effect of folding the liner. Two key parameters are defined for this study; the total length of the path d measured along the centre line in the folded cell, and the depth of the liner d_1, as shown in Fig. 7. The idea is that the folded liner may behave like a shallow liner of depth d_1 for relatively high frequencies while it may work like a deep straight liner of depth d for low frequencies. The width of the cell was kept constant to 5cm. Also in this study the fluid density ρ and the speed of sound c are fixed to $1.2kg/m^3$ and

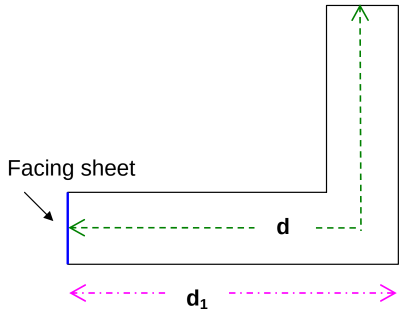

Figure 7: Folded liner, total path length d and the depth d_1

$340.0m/s$, respectively.

Liner impedance and diffuse field incidence absorption coefficients

The incident plane wave with unit pressure amplitude was specified at the source plane, and the complex amplitude of the reflected wave at the same plane was extracted from the ACTRAN results. By using the complex amplitudes of incident wave A and reflected wave B and the distance between the source plane and the surface of the liner L, the liner impedance Z_{liner} can be calculated by

$$\frac{Z_{liner}}{\rho c} = R + i\chi = \frac{Ae^{-ikL} + Be^{ikL}}{Ae^{-ikL} - Be^{ikL}}, \quad (3)$$

where R and χ are non-dimensional resistance and reactance.

The acoustic performance was assessed by using the diffuse field incidence absorption coefficient, calculated by the expression obtained for locally reactive uniform impedance surface [3],

$$\begin{aligned} \alpha_{diffuse} &= 8\Gamma[1 - \Gamma\ln(\frac{R}{\Gamma} + 2R + 1) \\ &\quad + (\Gamma\frac{R}{\chi})\{(\frac{R}{\chi})^2 - 1\}\arctan(\frac{\chi}{R+1})] \end{aligned} \quad (4)$$

where

$$\Gamma = \frac{R}{R^2 + \chi^2}. \quad (5)$$

Results

The diffuse field incidence absorption coefficients obtained for a folded liner with $d = 0.50$m and $d_1 = 0.05$m are shown with the same coefficients for straight SDOF liners of the depth 0.50m and 0.05m in Fig. 8. The analysis was performed for the frequency range 20Hz to 5kHz at 10Hz step. It can be said that the absorption coefficient of the folded liner behaves almost exactly the same as that of the straight liner of depth 0.50m at the lowest frequency range. As the frequency becomes higher the folded liner curve gradually leaves from the 0.50m straight liner one and approaches to the curve for the straight liner of depth 0.05m. In the current cases the absorption coefficient of the folded liner is quite similar to that of the 0.05m straight liner, except for several very sharp fluctuations.

Figs. 9 and 10 show the same sort of comparisons to investigate the folded liners of $d_1 = 0.15$ and $d_1 = 0.30$, respectively. The total path length d for the folded liners is kept constant t0 0.5m.

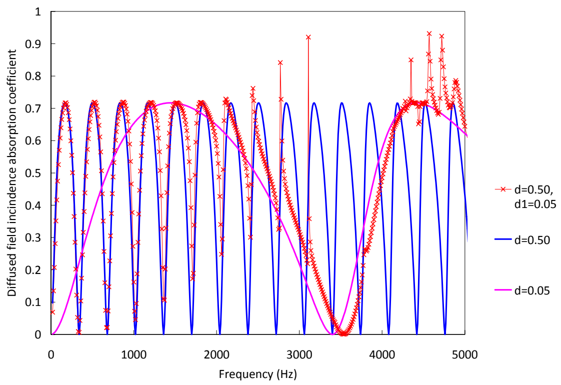

Figure 8: Diffused field absorption coefficient of folded liner $d = 0.50, d_1 = 0.05$ compared to straight SDOF liners of $d = 0.50$ and $d = 0.05$

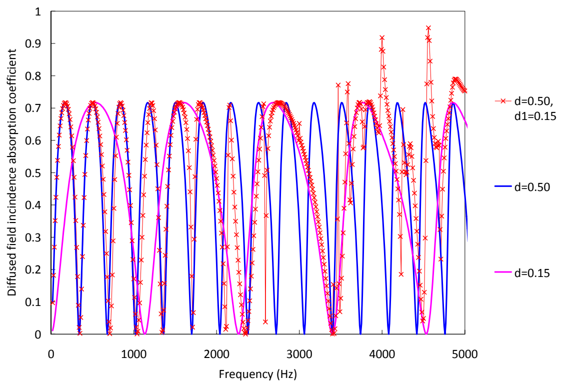

Figure 9: Diffused field absorption coefficient of folded liner $d = 0.50, d_1 = 0.15$ compared to straight SDOF liners of $d = 0.50$ and $d = 0.15$

The same tendency that the folded liner behaves like simply a deep liner of the depth d for low frequencies while its behaviour changes towards that of a shallow liner of the depth d_1 for high frequencies.

Fig 11 shows an example of the real part of acoustic pressure at 400Hz in the FE domain. It can be seen that in case of low frequency the acoustic wave propagates towards the end of the liner ignoring the bent.

SUMMARY

The acoustic behaviour of folded liner was studied by using finite element analysis which models the impedance tube and a liner cell. The absorption coefficients obtained for folded liners were compared with straight SDOF liners which have the depth corresponding to one of critical dimensions of the folded liner. The results indicate that at low frequencies a folded liner behaves as a deep liner which is the length of the total path along the centre line deep, while at high frequencies it behaves like a shallow liner which is equivalent to having the depth of the distance between the facing sheet and the bottom of the folded liner.

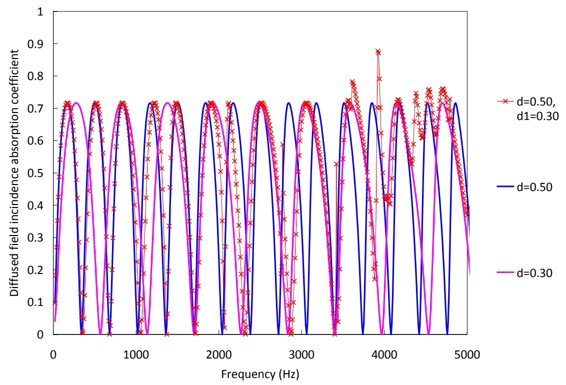

Figure 10: Diffused field absorption coefficient of folded liner $d = 0.50, d_1 = 0.30$ compared to straight SDOF liners of $d = 0.50$ and $d = 0.30$

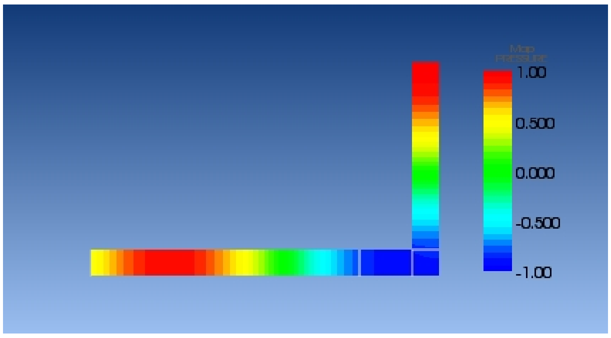

Figure 11: Real part of acoustic pressure at 400Hz, folded liner $d = 0.50, d_1 = 0.15$

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