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# ACOUSTICS 2012

## Laboratory investigations of low frequency sound attenuation over combustion flat perforated wall sheet

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Steel perforated liners have been used in turbine combustors for many years. The main purpose of the holes on the combustion chambers is to cool the combustor wall by inducing cooling air flows through them. In addition, it would be useful if the steel perforated liners could be used for attenuating the combustion noise, especially for low frequency noise. This paper presents a series of acoustic relative resistance measurements which were carried out in a 500 mm (width)  $\times$  500 mm (height)  $\times$  6000 mm (length) impedance tube on flat perforated steel plates with various geometric parameters. The results from the measured absorption coefficient and impedance show that the steel perforated plates have strong sound attenuation on a certain frequency bandwidth. Experimental data were compared with predicted data that concerned the effects of air inertia and viscosity in apertures. The results show reasonable agreement with the prediction values. The acoustic attenuation properties, inferred from normal surface resistance and absorption coefficient data on perforated panels with different plate thicknesses, perforation ratio, hole diameter, hole distribution and double-layer plate are presented. The measurement results and analyses show that with careful design the cooling holes on the combustor wall can be used to attenuate the noise efficiently.

## 1. Introduction

A combustion soft wall is basically a double layer steel cylindrical sheet with small diameter holes distributed in the chamber wall. The diameters of the holes usually range from 0.8 mm to 5.0 mm to let air flow through. The main purposes of a perforated soft wall in a turbine combustor are: (1) to decrease the main flame emission effect, (2) to reduce the effect on the turbine inlet temperature profile and (3) to increase cooling and to prolong the life of the combustor [1].

In order to investigate sound attenuation properties of the steel perforated wall, different flat steel plates with laser-drilled small holes were measured in a 500 mm (width)  $\times$  500 mm (height)  $\times$  6000 mm (length) impedance tube. In the impedance tube, the acoustic attenuation properties of a full scale sheet of the combustion wall of a 500 mm  $\times$  500 mm perforated area with several thousand small holes can be tested. Hughes and Dowling (1990) investigated the effects of curvature on the absorptive properties of a liner and showed that a highly absorptive liner can be designed by assuming that it is planar provided that the azimuthal variation in the sound field is small [2].

In this paper the plates' surface relative impedance and absorption coefficient measurement results show that the steel perforated plates with hole diameters at 0.85 mm and 1.10 mm have strong sound attenuation, and combining this with careful acoustic design, a combustion perforated wall can be used to effectively reduce the combustion noise.

Micro-perforated panels (MPP) have been studied for many years. A typical MPP usually has sub-millimetre diameter holes and plate thickness roughly equals the hole diameter. A MPP sound absorber is designed to have enough acoustic resistance and low acoustic mass reactance for wide-band sound attenuation. Double layer MPPs have also been developed [5, 6, 7, 10] to broaden the sound absorption band.

Although theories and measurements for micro-perforated plate absorbers have been well established, it appears that no analyses and impedance tube low frequency tests have been carried out for (1) thick (relative to the diameter of hole), (2) heavy (surface density can be as high as 24 kg/m<sup>2</sup>) steel plates with (3) extremely low porosity (0.26%), over (4) a large perforated area (0.5 m  $\times$  0.5m).

## 2. Experimental apparatus and samples

Impedance measurements were carried out on seventeen perforated steel plates (their geometric parameters shown in Table 1). The parameters were chosen according to the requirements for a perforated sheet of a gas turbine combustor line. As described early, an ideal acoustic micro-perforated plate is usually designed to be thin (sub-millimeter) and light [5], so can be treated as a tension-free membrane. The 2-3 mm thickness of the plates and the strong stainless steel material used in our experiments may imply that the stiffness of the plates cannot be ignored in the sound attenuation analyses.

Table 1: Plate geometric parameters.

Plate thickness t (mm)	Hole diameter d (mm)	Plate perforation $\sigma$ (%)	Hole distribution	Axial pitch of hole (mm)
2.0	0.85	0.86	(1)	10.5
3.0	1.10	0.51	Uniform	
	3.64	0.43	(2)	
		0.26	Concentrated	21.0

The sound absorption coefficient and relative impedance of the perforated plates were measured in a large concrete impedance tube which enabled this research to focus on frequencies lower than the cut-off frequency 400 Hz. The sound attenuation performance of the steel perforated plates at low frequency is of particular interest in the combustor design as the acoustically induced motion will play an important role in potentially causing fatigue damage of the chamber. Therefore, a 500 mm  $\times$  500 mm  $\times$  6000 mm low frequency impedance tube was used. The tube was built with 75mm thick concrete walls with a 100 kg rigid smooth steel cap to reduce the acoustic motion at low frequencies. The measurements were carried out using the two-microphone transfer function technique [8]. To measure the sound pressure at different locations in the tube simultaneously, two B&K 4190 ½ inch microphones were connected to a two-channel National Instruments data acquisition card.

The cavity depths behind the plate were selected at 55 mm, 63 mm and 68 mm. Measurements of impedance and absorption coefficient for double layer perforated plates were also carried out in the impedance tube. The gaps between the two plates were 5 mm and 10 mm.

### 3. Comparison of measurements to predicted impedance and absorption coefficient

#### 3.1 Predicted perforated plate impedance

According to Maa's theory [3], the relative acoustic impedance  $z$  of a perforated plate under a normal incident plane wave can be calculated by

$$z = r + j\omega m \tag{1}$$

where

$$r = \frac{32\eta}{\sigma\rho c} \frac{t}{d^2} k_r \tag{2}$$

$$\omega m = \frac{\omega t}{\sigma c} k_m \tag{3}$$

$$k_r = \left(1 + \frac{k^2}{32}\right)^{\frac{1}{2}} + \frac{\sqrt{2}}{32} \frac{d}{t} k \tag{4}$$

$$k_m = 1 + \left(9 + \frac{k^2}{2}\right)^{\frac{1}{2}} + 0.85 \frac{d}{t} \tag{5}$$

$$k = d \sqrt{\frac{\omega\rho}{4\eta}} \tag{6}$$

where  $d$  is the hole diameter,  $\rho$  is the density of air,  $\eta$  is the dynamic viscosity,  $\omega$  is the angular frequency,  $\sigma$  is the panel perforation,  $c$  is the sound speed and  $t$  is the panel thickness.  $k$  is the perforation constant which is a type of ratio of inertia of the air in the aperture to the viscous boundary layer thickness in the aperture. Perforation constant increases with frequency as presented in Eq. (6). The equations (1) – (6) are dealing with the geometry of the panel and it is assumed the plate is immobile.

Fig. 1 shows that the hole perforation constant varies with hole diameters 0.85 mm, 1.10 mm and 3.64 mm over 0-500Hz. The figure illustrates that the perforation constant increases with frequency and the hole diameter. The plate with 3.64 mm diameter holes has a higher value of  $k$  than the plates with 1.1 mm and 0.85 mm diameter holes. Since the absorption band narrows down quickly when  $k$  is increased [3], therefore the plate with 3.64 mm diameter holes has a lower sound attenuation.

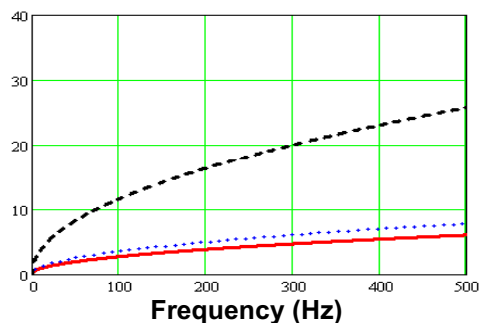


Figure 1: Perforation constant  $k$  with: ----- 3.64 mm diameter, ..... 1.1 mm diameter and ——— 0.85 mm diameter holes

For a combustion perforated wall, since it works under high temperatures around 1500 K, the air has a much higher dynamic viscosity  $\eta$  and a lower density  $\rho$  compared to air at normal temperature. According to Eq. (6), an extremely small perforated constant  $k$  can be obtained for a combustor perforated liner. Consequently, with careful design, the combustor liner would attenuate the noise efficiently.

#### 3.2 Absorption coefficient of a perforated plate with a cavity

When a perforated panel is fixed in front of a rigid cavity which has a smooth rigid surface parallel to the perforated plate, the relative acoustic reactance of the cavity is  $-\cot(\omega D/c)$ , where  $D$  is the depth of the cavity. For normal incidence sound pressure on the surface of the plate, which is the case for a tested plate in the impedance tube under a plane wave region, the absorption coefficient  $\alpha$  of the panel-cavity system is

$$\alpha = \frac{4r}{(1+r)^2 + (\omega m - \cot(\omega D/c))^2} \tag{7}$$

Equation (7) shows that the system reactance consists of the air mass inertial reactance in the apertures ( $\omega m$ ) and the reactance of the air in the cavity ( $-\cot(\omega D/c)$ ). Clearly, the absorption coefficient  $\alpha$  has a maximum value of  $4r/(1+r)^2$  when  $\omega m - \cot(\omega D/c)$  equals zero. Therefore the peak value of the absorption coefficient  $\alpha$  is defined by the resistance of the plate only and independent of the cavity depth.

#### 3.3 Comparison of measurement to prediction

Eqs. (1) - (7) were used to compare the measurement results obtained from the large concrete tube. Fig. 2 shows comparison of the measured impedance and the predicted impedance. Fig. 3 shows comparison of a measured absorption coefficient and predicted absorption coefficient of the sample plate. The perforation plate used for the test consisted of 2.0 mm thick stainless steel and had 0.85 mm diameter holes in the plate. The perforation of the plate was 0.51%.

In Fig. 2, the predicted relative impedance fitted quite well with the measured value at frequencies higher than 220 Hz. At frequencies lower than 220 Hz, the measured relative resistance is higher than the predicted values, whilst at frequencies lower than 150 Hz, the measured reactance is lower than the predicted values. In Fig. 3, the predicted absorption coefficient had lower values than the measurement values at frequencies below 230 Hz. A small peak at 220 Hz in the absorption coefficient spectrum was observed in the measurements, which does not appear in the predicted absorption coefficient.

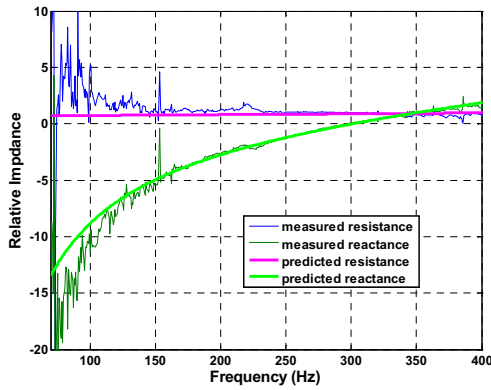


Figure 2: Comparison between the measured (thin line) and predicted (thick line) relative impedance.

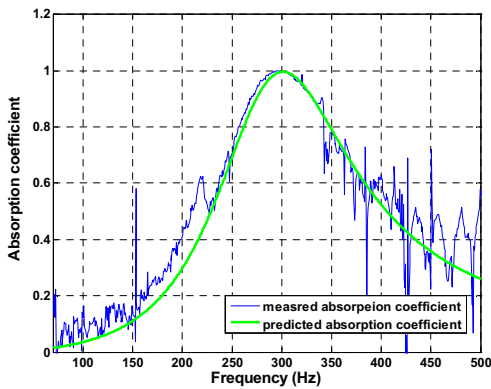
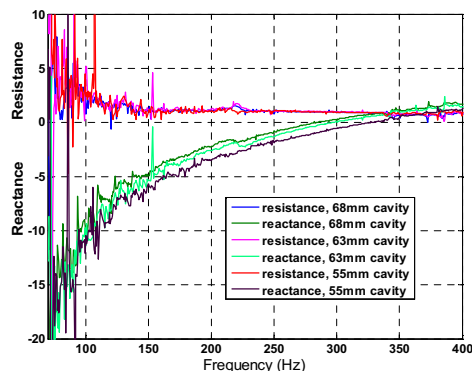


Figure 3: Comparison between the measured (thin line) and predicted (thick line) absorption coefficient.

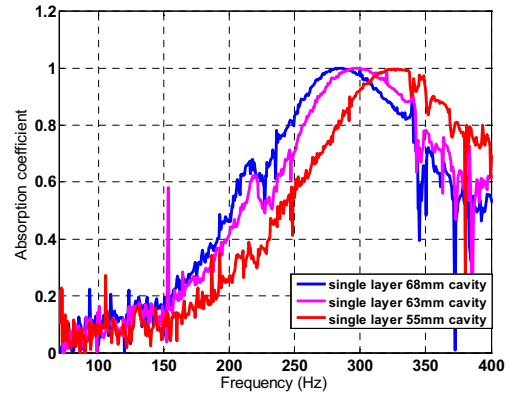
### 4. Relative resistance and perforated plate parameters

The maximum absorption coefficient and maximum possible absorption bandwidth were decided by the value of relative resistance  $r$  [3].

According to Eq. 2, the plate relative resistance  $r$  does not vary with the change in cavity depth behind the perforated panel. The measured relative impedance over a plate with cavity depth 55 mm, 63 mm and 68 mm in Fig. 4(a) represented the stability of the relative resistance. However the corresponding total relative reactance  $\omega m - \cot(\omega D/c)$  and absorption coefficient shifted with the cavity depths, as shown in Figs. 4(a) and 4(b), respectively.



(a)



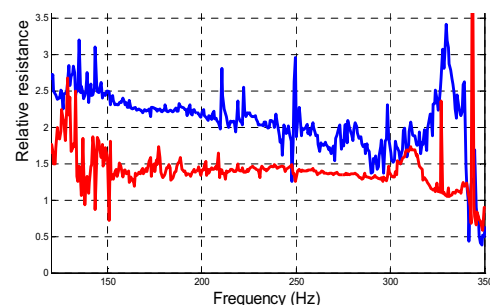
(b)

Figure 4: (a) Measured relative impedance; and (b) measured absorption coefficient, at cavity depth 55 mm, 63 mm and 68 mm.

To investigate the sound absorption of the perforated combustion wall, a series of perforated plates were tested (see table 1). The relative resistance of the impedance can be directly measured and closely correlated with the absorption and geometry sizes such as: plate thickness, hole diameter, plate perforation, hole distribution and the axial pitch of the holes. In addition,  $r$  is relatively stable and does not vary with different working conditions, for instance working as a single sound plate absorber or as a resonator attenuator that is attached to a cavity. It is a quantity that represents the perforated plate sound attenuation. Clearly, by combining with plate-cavity reactance which varied with working conditions, the final sound attenuation performance of the perforated plate can be obtained by using Eq.7. Consequently, the following analyses will focus on the relative resistance which should indicate the acoustic performance of the perforated wall in a combustor more clearly.

#### 4.1 Plate perforation

The plate perforation is defined as the ratio of total hole area to the plate area. The perforations of the measured plates were 0.86%, 0.51%, 0.43% and 0.26%. In Figs. 5 (a) to (d), each figure shows measured relative resistances of the two plates with the same plate geometric parameters except for plate perforation. The measurement results with different plate thicknesses and different hole diameters show that the plate resistance increases with decreasing plate perforation. However, reduced perforation will increase the pressure drop and decrease the flow rate of the cooling flow through the combustor wall too.



(a)

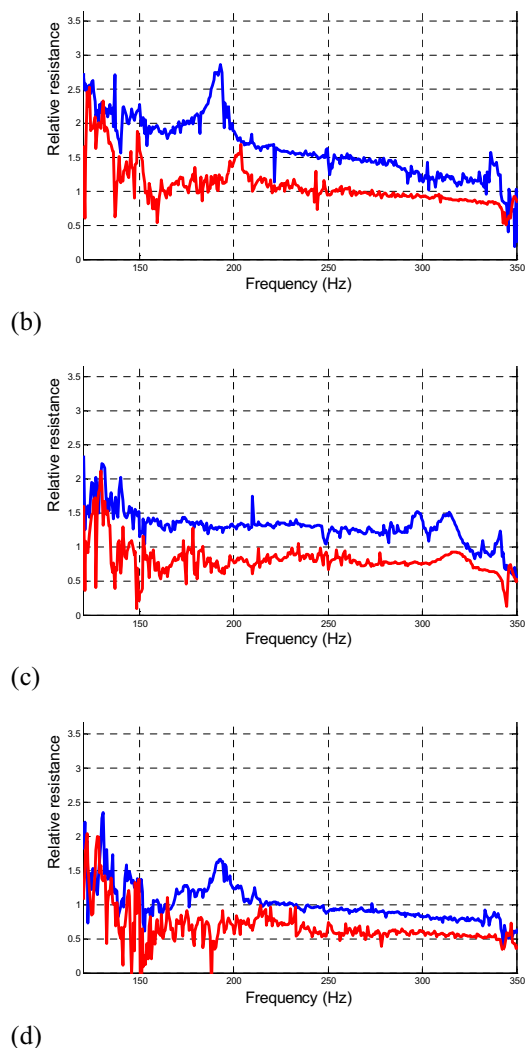


Figure 5: Comparison between measured relative resistance and plate perforation (a)  $\sigma = 0.26\%$ ,  $\sigma = 0.51\%$ ,  $t = 3.0$  mm,  $d = 0.85$  mm, (b)  $\sigma = 0.26\%$ ,  $\sigma = 0.51\%$ ,  $t = 2.0$  mm,  $d = 0.85$  mm, (c)  $\sigma = 0.43\%$ ,  $\sigma = 0.86\%$ ,  $t = 3.0$  mm,  $d = 1.10$  mm, (d)  $\sigma = 0.43\%$ ,  $\sigma = 0.86\%$ ,  $t = 2.0$  mm,  $d = 1.10$  mm.

In Figs. 5(a) to (d), there are noticeable peaks in the resistance spectra. The magnitude of the peak increases with reduction in the perforation. As shown in Fig. 5(a), the strongest peak magnitude was measured over a plate with 0.85 mm hole diameter, 3.0 mm thickness and 0.26% perforation, which also had the highest relative resistance. The weakest peak magnitude was observed in Fig. 5(d) over a plate with 1.10 mm hole diameter, 2.0 mm thickness and 0.86% perforation, which had the lowest relative resistance. It became apparent that the peak amplitude was closely related to the plate resistance values. On the other hand, the location of the peak frequency varied with different thicknesses of the plate. For plate thicknesses of 2.0 mm and 3.0 mm, the peak frequencies were around 180 Hz (Fig. 5(b)) and 320 Hz (Fig. 5(a)) respectively.

To get a higher resistance, the perforation is comparably low. The particle velocity through the micro pores attains a high value even at moderate sound pressure. The high velocity of the air particles may form a jet at the exit of the micro pores and this will significantly increase the

resistance of acoustic impedance of the panel and hence affect the absorption properties of the perforated plate [9].

### 4.2 Hole diameter

Hole diameters of 0.85 mm and 1.10 mm were used for the comparison tests.

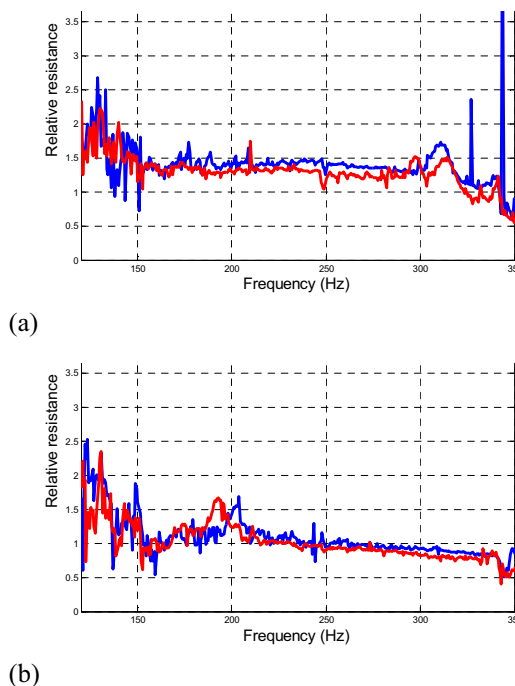
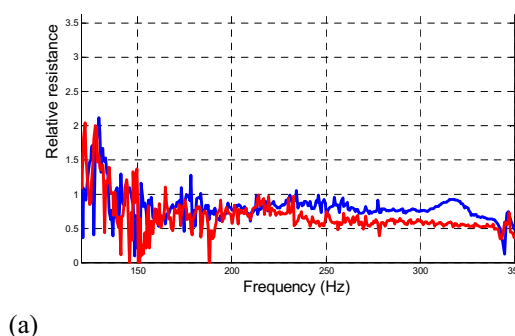


Figure 6: Comparison between measured relative resistance and hole diameter, (a)  $d = 0.85$  mm,  $\sigma = 0.51\%$ ,  $d = 1.10$  mm,  $\sigma = 0.43\%$ ,  $t = 3.0$  mm, (b)  $d = 0.85$  mm,  $\sigma = 0.51\%$ ,  $d = 1.10$  mm,  $\sigma = 0.43\%$ ,  $t = 2.0$  mm.

Fig. 6(a) shows the resistance measured over two plates. The first plate had 3.0 mm thickness, 0.51% perforation and 0.85 mm hole diameter and the second plate had 3.0 mm thickness, 0.43% perforation and 1.10 mm hole diameter. The analysis in section 4.1 shows that the plate with 0.43% perforation should have a higher resistance than the plate with 0.51% perforation when the hole diameters are the same values. However, the measurement results in Fig.6(a) show that the plate with smaller hole diameter 0.85 mm had higher resistance than the plate with 1.10 mm hole diameter, although the 0.85 mm diameter plate has a higher perforation than the 1.10 mm plate. Similar measurement results shown in Fig. 6(b) present that the relative resistance increases with decreasing hole diameter.

### 4.3 Plate thickness





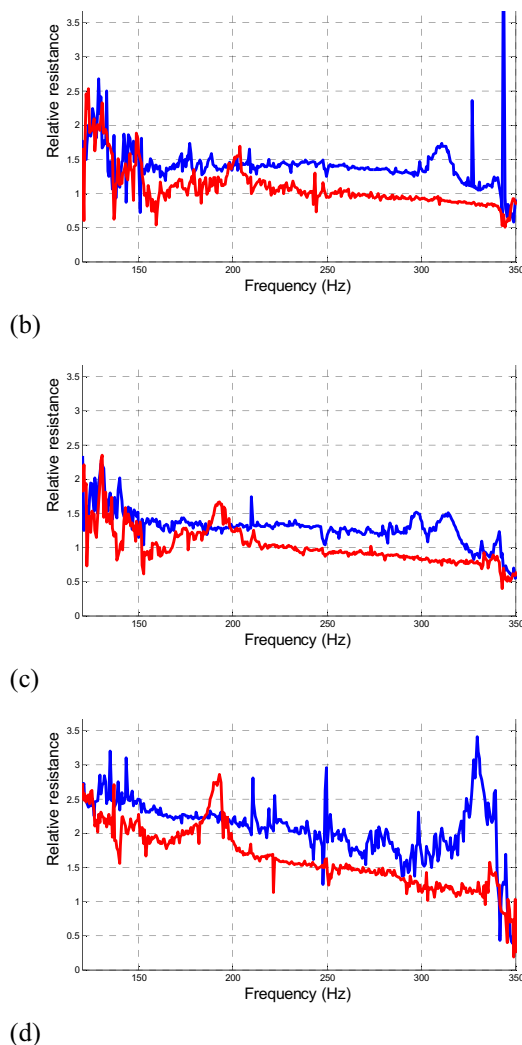


Figure 7: Comparison between measured relative resistance and plate thickness —  $t = 3.0$  mm and —  $t = 2.0$  mm, (a)  $\sigma = 0.86\%$ ,  $d = 1.10$  mm, (b)  $\sigma = 0.51\%$ ,  $d = 0.85$  mm, (c)  $\sigma = 0.43\%$ ,  $d = 1.10$  mm, (d)  $\sigma = 0.26\%$ ,  $d = 0.85$  mm.

In each figure from Figs. 7(a) to (d), there are two resistance spectra that were measured over two plates with the same plate geometric parameters except for plate thickness (2.0 mm and 3.0 mm). The resistance spectra indicate that the resistance increases with increased plate thickness. Measurements over different plate perforations of 0.86%, 0.51%, 0.43% and 0.26% (Figs. 7(a)-(d)) present the consistent effects of the plate thickness. The strongest thickness effects were obtained over the 3.0 mm plate with perforation 0.26% (Fig. 7(d)) and the lowest effects due to thickness were over the 2.0 mm plate with perforation 0.86% (Fig. 7(a)). It is believed that lower perforation has a higher pressure drop through the air path. Consequently, more energy is dissipated by the interaction effects of fluid-fluid and fluid-plate along a longer air path when the perforation is lower.

The effect of increasing the plate thickness is equivalent to increasing the length of the air path in the perforated plate. Plate resistance represents two forms of energy loss, (1) the viscosity of the air in the hole path [4] and (2) the contraction and expansion of the air stream when it enters and exits the hole [9] respectively. Increasing the plate thickness mainly increases the effect of the viscosity energy loss along the hole path. To increase the total resistance, it

would be more effective to have an additional layer on the perforated plate, which increases the energy loss at both the hole path and the path ends, rather than simply increasing the thickness to form a single thick layer.

#### 4.4 Hole distribution

Fig. 8 shows two plates have the same overall perforation of 0.43% but plate (a) has an even hole distribution on an area 500 mm  $\times$  500 mm and plate (b) has all holes evenly concentrated in a central square area 345 mm  $\times$  345 mm. The measured relative resistance spectra are shown in Fig. 9. There is an apparent strong peak at 220 Hz over the plate containing the concentrated perforated area. The peak might be induced by the motion of the plate.

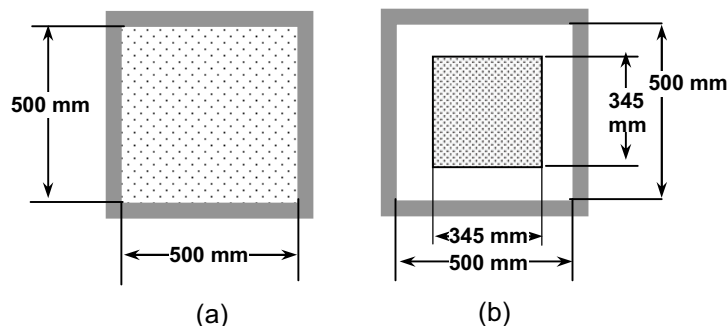


Figure 8: (a) Evenly distributed hole area,  $\sigma = 0.43\%$  and (b) concentrated hole area,  $\sigma = 0.43\%$ .

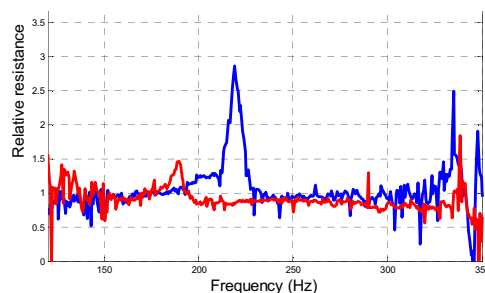
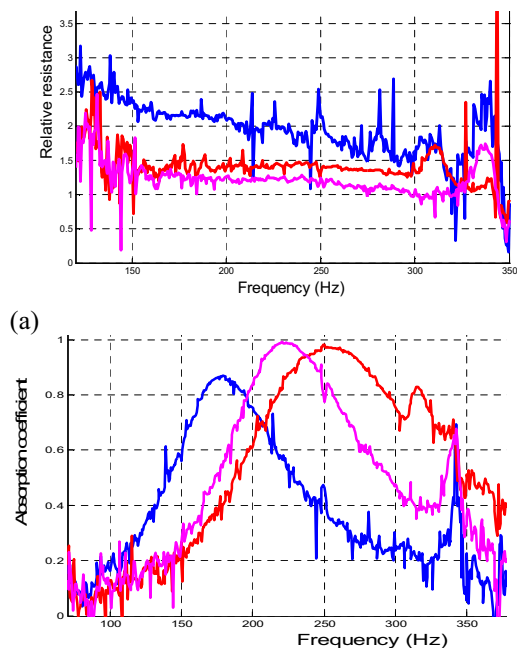


Figure 9: Comparison between measured relative resistance and hole distribution — hole evenly distributed over area 500 mm  $\times$  500 mm and — hole evenly distributed over area 345 mm  $\times$  345 mm,  $\sigma = 0.43\%$ ,  $d = 1.10$  mm,  $t = 2.0$  mm.

#### 4.5 Double layer perforated plate

Fig. 10(a) shows that (1) the measured relative resistance of a double layer perforated plate with 5 mm gap, and (2) the two resistance spectra of the corresponding single layer plates. It is clearly shown that at the lower frequency of 120 Hz, the double layer resistance roughly equals the sum of the resistances of the two corresponding signal layers. At the higher frequency 300 Hz, the double layer resistance is close to one single layer resistance. Fig. 10(a) also presents two peaks at around 310 Hz and 340 Hz which appears in the two single layer resistance spectra separately. Generally, the double layer resistance decreases with increasing frequency and has a maximum value equal to the sum of the two single layer resistances.



(a) Comparison between measured relative resistance over double layer and single layer perforated plate, plate 1:  $\sigma = 0.51\%$ ,  $d = 0.85$  mm,  $t = 3.0$  mm, plate 2:  $\sigma = 0.43\%$ ,  $d = 1.10$  mm,  $t = 3.0$  mm. —  $r$  over double layer with 5 mm gap between the plates; —  $r$  over single plate 1; —  $r$  over single plate 2; (b) —  $AC$  over double layer with 5 mm gap between the plates; —  $AC$  over single plate 1; —  $AC$  over single plate 2.

Fig. 10(b) represents the measured absorption coefficient of the double layer structure attached to a 55 mm rigid cavity. The results show the double layer perforated plates increase the sound attenuation at frequencies lower than around 200 Hz but decrease sound attenuation at frequencies higher than around 200 Hz. This observation is consistent with the measurements and analyses of other authors [5, 6, 10] for thin lightweight micro perforated plates. However there was no ‘double peak’ observed in the measured double layer absorption coefficient that was reported by other researchers [5, 10].

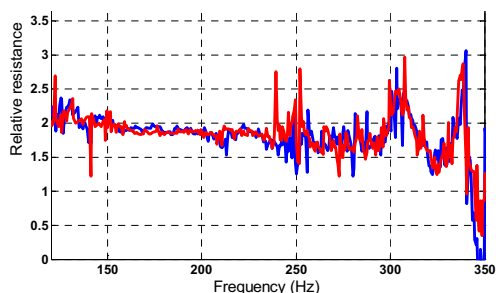


Figure 11: Measured relative resistance over double layer perforated plate, plate 1:  $\sigma = 0.26\%$ ,  $d = 0.85$  mm,  $t = 3.0$  mm, plate 2:  $\sigma = 1.50\%$ ,  $d = 3.64$  mm,  $t = 1.5$  mm. —  $r$  over double layer with 5 mm gap between the plates; —  $r$  over double layer with 10 mm gap between the plates.

Fig. 11 presents measured resistance of a double layer perforated plate at 5 mm and 10 mm gaps between the two layers. The measured results show there is no apparent difference between the resistances at 5 mm and 10 mm gaps.

## Conclusions

In conclusion, it has been shown that the laboratory results have given satisfactory descriptions of the sound attenuation effects of the steel perforated plates on the surface impedance and absorption coefficient. The measurements were also found to be consistent with theoretical models. In addition, it was noticed that multiple peaks in the relative resistance spectra can be formed due to acoustically-induced structural motion. Overall, these results and analyses indicated that a combustor wall with cooling holes can be used to efficiently attenuate combustion noise.

## Acknowledgement

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