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Acoustics and Sustainability:

How should acoustics adapt to meet future demands?

An improved plenum chamber silencer

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ABSTRACT

An expansion chamber functions as a silencer due to a change of acoustic impedance at each end of the silencer. A common disadvantage of this type of silencer is that the air flow is impeded, which results in a pressure drop between inlet and outlet. Porous absorptive material can improve the acoustic performance of an expansion chamber silencer (making it function as a combined dissipative and reactive silencer), but has limited practical applications (due to potential clogging of the absorber with particles, and entrainment of absorber fibbers in the airflow) and does not solve the problem of pressure loss. This study examines the performance of a lined expansion chamber that has a thin membrane arranged so that the free air flow cross section does not change. The advantage of this arrangement is that there is little pressure drop compared to the simple expansion chamber, and acoustic performance is similar to that of the chamber with porous absorber, but without the associated problems. It also allows the use of more effective linings such as graded density ones which are easily damaged by airflows.

1. INTRODUCTION

Many silencer designs perform well as acoustic attenuators but their designs compromise the flow performance of the silencer. This is generally due to their geometrical design, which inhibits a direct or clean flow path. A simple example of these design issues can be portrayed by the plenum chamber. As simple as the design is, the acoustic performance is high, but the pressure drop across the silencer is also high. The rapid change in cross sectional area and the offset of the inlet and outlet cause a high pressure drops across the system.

In order to achieve a design in which services both requirements of low pressure drop and high acoustical absorption, an analysis of the factors which cause these two requirements has to be made.

This paper investigates the design of a silencer that incorporates a membrane between the inlet and outlet of the silencer, which aids in the flow of gases through the system. This design smoothes the flow through the system, whilst still allowing the acoustic performance to remain high.

The other benefit of this silencer arrangement is the cost of production. Due to the simplistic design the cost of mass producing this product should be low.

2. DESIGN PROPERTIES IN ORDER TO AID FLOW

A major factor which makes this silencer different to other designs is its emphasis in the design to aid fluid flow. Generally, as a design changes to benefit the acoustic performance the flow performance decreases. An increase in flow performance can be understood by understanding the behaviour of air-flow and its properties

2.1. Fluid characteristics

When a fluid is forced to suddenly change direction or enter an area of differing cross section, it forces changes in the energy of the fluid, as some of that energy is lost in the turbulence of the change. This causes a back pressure through the system which may have an adverse effect on its performance. Turbulence can be decreased by ensuring gradual changes in the flow but in order to reactively reduce noise there must be sudden changes in geometry

3. PLENUM DESIGN AND ARRANGMENT

The concept of a plenum chamber is commonly understood in the engineering community. The geometrical shape of the plenum chamber characterizes its strong performance as an acoustic attenuator. The diagram in figure (1) shows the plenum chamber design which was used for the experimentation, note positions of inlet and outlet.

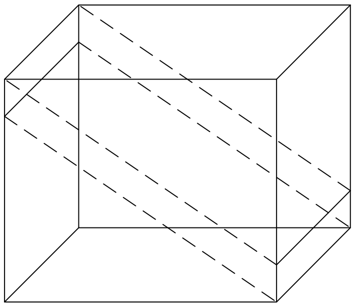

Fig.1. Plenum chamber design with membrane illustrated in broken line

The cross sectional change in area of the duct provides the plenum chamber with a portion of its acoustical absorption properties, but hinders the flow of gases through the system. In order for this design to aid the flow, two membranes are placed between the inlet and discharge of the plenum as shown in Figure (1). The width of the passage formed by the membranes was equal to the width of the inlet and discharge ducts, as a result there is no expansion or contraction as the air passes through the silencer.

3.1 Membrane placement

The membrane was stretched between the inlet and outlet of the plenum chamber. For the flow to be aided by the presence of the membrane, it is important that the membrane is taut, as any looseness would result in an incresed pressure drop.

4. PRESSURE DROP

Throughout this article the phrase pressure drop will be used to describe the total pressure loss across a certain section of duct; this will be referred to as Δp.

By introducing a change in direction, roughness or cross sectional area a pressure drop will occur. The total pressure losses in a system can be calculated by the equation, (eqn. 1).

$$\Delta p = \left(\frac{fL}{D_h} + \sum K\right)\left(\frac{\rho V^2}{2}\right) \tag{1}$$

Where Δp (Pa) is the pressure drop, f (dimensionless) is the friction coeficient, L (m) is the length of duct, Dh (m) is the hydraulic diameter, K (dimensionless) the loss coefficient for various components in the system, V (m/s) is the velocity and ρ (kg/m³) is the density of the gas of the flow.

The dimensionless loss coefficient K is used to calculate the total pressure loss across a component of the system. The loss coefficient represents the ratio of total pressure loss (Δp) across a component of the system to velocity pressure ($\frac{1}{2}\rho V^2$) at a referenced cross section. Empirical values for loss coeficients are specified in (ASHRAE, 2001), (Idelchik, 1993) and (Miller, 1990). The value will vary with the degree of change in direction or area.

The hydraulic diameter of a duct or section of duct can be derived by applying the formula in (eqn. 2)

$$D_h = \frac{4A}{P} \tag{2}$$

Where A (m²) is the area and P (m) is the perimeter of the duct.

The friction coefficient can be calculated from the Altshul–Tsal equation (eqn. 3).

$$f = 0.11\left(\frac{\varepsilon}{D_h} + \frac{68}{\mathrm{Re}}\right)^{0.25} \tag{3}$$

Where ε is the material absolute roughness in (m) and Re is the Reynolds number.

Reynolds number is derived from the formula in equation (eqn 4)

$$\mathrm{Re} = \frac{D_h V}{1000\nu} \tag{4}$$

Where Re is the Reynolds number, Dh (m) is the hydraulic diameter, V (m/s) is the velocity in and ν (m²/s) is the kinematic viscosity.

This data will be used to estimate the losses in a plenum chamber and a similar plenum chamber with membranes inserted.

4.1. Calculated pressure drop over plenum chamber with and without membrane

To predict the pressure drop for the silencer, it has been considered in three sections: the inlet, which will have a specific K value for the degree of change in angle, the membrane lined duct with the frictional losses to be calculated and the outlet which also has a specific K value. Equation (1) can be separated into three sections to derive the losses in each part of the silencer.

$$\Delta p_f = \frac{fL}{D_h} \times \frac{\rho V^2}{2} \tag{5}$$

Equation (5) gives the membrane frictional losses, with f the coeficient friction of the membrane, L the length of the membrane lined passage and Dh the hydraulic diameter of the passage.

The friction coefficent can be derived using equation (3) which takes into account the absolute roughness of a specific material. The absolute roughness factor was obtained from (ASHRAE,2001) and (Idelchik, 1993).

$$\Delta p = (K_{inlet} + K_{outlet}) \times \frac{\rho V^2}{2} \tag{6}$$

Equation (6) represents the inlet and discharge pressure losses of the silencer.

The plenum chamber inlet loss was taken as one inlet duct velocity head and the exit loss K as 0.5 from (Idelchik, 1993) Diagram 3-10.

For the plenum chamber with the membrane fitted the inlet and discharge bend (45 degrees, aspect ratio 5.29) loss factor K is given as 0.23 (Idelchik, 1993) Diagram 6-7, 0.26 by (ASHRAE, 2001) Table CR3-6 and 0.29 by (Miller, 1990) Figure 9.9. A conservative value of 0.30 was used.

Table 1 presents the data used to predict the pressure drop.

Membrane Plenum Chamber

	K	Friction factor
Inlet	0.3	n/a
Outlet	0.3	n/a
Membrane	n/a	0.000005

Plenum chamber

	K
Inlet	1
Outlet	0.5

Table. 1. Coeficients for pressure drop predictions

Once the constants are derived, the pressure drop for varying velocities can be calculated. The following figure graphically displays the predicted pressure losses for the plenum chamber tested with and without a membrane.

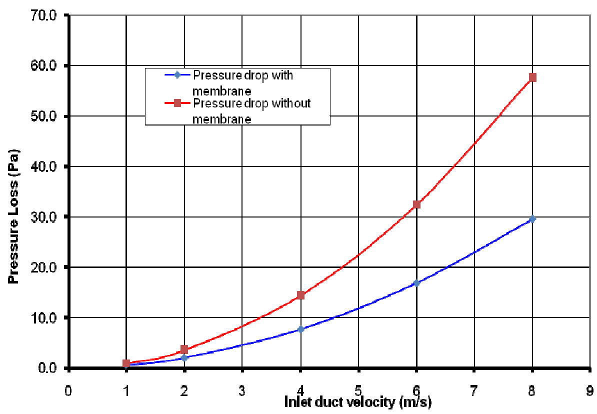

Fig. 2. Pressure drop predictions, with and without membrane

The figure (2) above shows the predicted benefit of applying the membrane to the silencer.

5. TESTING

In order to qualify the predicted results, a silencer test facility which allowed the ability to test flow as well as acoustic performance was required.

To achieve flow through the silencer the test rig was built to connect to an existing air supply duct which feeds air into the anechoic chamber at Sydney University Architecture Department. As the silencer inlet was only 1/27th the size of the air supply duct, a contraction, had to be designed to reduce the size of duct opening to that of the silencer inlet duct. The contraction allowed the test rig to operate at a higher flow velocity from what is a very low supply flow velocity to the chamber. The other benefit from the contraction was that it allowed the velocity distribution into the test rig to even out. Preliminary measurements had revealed that the velocity distribution at the duct outlet was very uneven due to an unvaned 90 degree bend prior to the outlet.

To test the acoustic parameters of the silencers, two loud speakers, were placed in the walls of the duct before the contraction to input noise.

Figure 3 shows the test arrangement.

Acoustic measurements were taken using pink noise as the noise source. Measurements were made with a Bruel and Kjaer 2250 sound level meter with the microphone positioned 150mm from the discharge duct outlet inline with the centre of the short side of the duct. The insertion loss was obtained from the difference in sound pressure levels at this position with and without the silencer in the test facility.

The static pressure loss across the silencer was measured using tappings located in the straight sections of duct before and after the silencer.

The flow through the silencer was measured by a 30 point pitot traverse in the duct upstream of the silencer. Silencers were tested with inlet duct velocities up to 7 m/s.

The acoustic attenuator which was tested had an inlet and discharge duct of 42mm by 222mm and the silencer plenum was 292mm high, 267.5mm in length and 222mm wide.

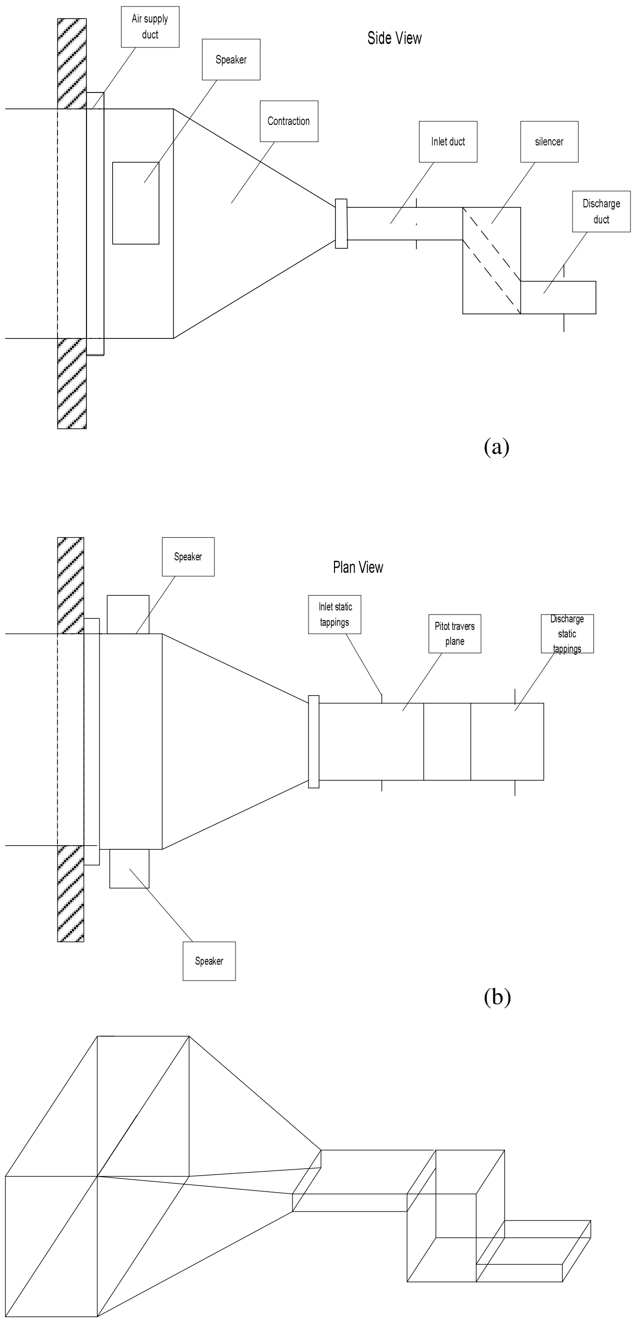

Fig. 3 Acoustic and airflow test rig

6. PLENUM CHAMBER ACOUSTIC PERFORMANCE

The simplest description of a plenum chamber is a length of duct followed by an abrupt change in cross sectional area followed by a second duct. The transmission loss of such a system can be represented by the equation below (Beranek 1988).

$$L_{TL} = 10\log\left[1+\frac{1}{4}\left(m-\frac{1}{m}\right)^2 \sin^2 kl\right] \quad dB \qquad (7)$$

Where m is equal to

$$m = \frac{\text{cross sectional area of chamber}}{\text{cross sectional area of duct}} = \frac{S_2}{S_1} \quad (8)$$

And *kl* is equal to

$$kl = \frac{2\pi l}{\lambda} \quad (9)$$

Where λ is the wave length and l equal to the length of the chamber.

By applying the formula in equation (7) a predicted insertion loss can be derived for the silencer tested.

Figure (4) gives a comparison between the calculated and measured insertion loss.

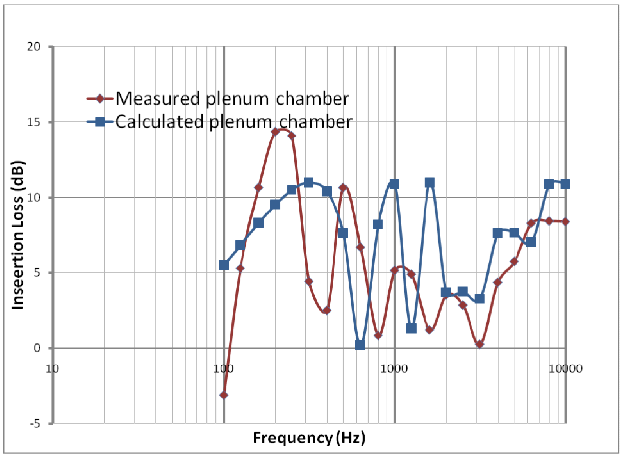

Fig. 4. Measured and calculated acoustic loss for the plenum chamber

The calculated results have a similar trend to the results measured in the test facility although there are significant differences in both the peak insertion loss values and the frequencies at which they occur. The average insertion loss values are similar.

6.1. Plenum chambers and absorbent lining

An absorptive lining added to a plenum chamber can be very beneficial to acoustic performance. The classification of the silencer changes, as now it would be referred to as reactive/ dissipative. The performance of such a silencer is directly proportional to the density and thickness of the lining. A significant increase in broadband attenuation is achieved and the high peaks and low troughs, characteristic of reactive silencers, are evened out. The present silencer design utilizes the broadband effectiveness of the lining to achieve a greater sound attenuation.

The attenuation through a lined plenum chamber can be calculated using equation (10) (Beranek 1988)

$$L_{TL} = -10\log\left[s\left(\frac{\cos\phi}{2\pi q^2} + \frac{1-\bar{\alpha}}{\alpha}\right)\right] \quad (10)$$

Where S (m²) is equal to the area of the outlet, $\bar{\alpha}$ (dimensionless) is random-incidence absorption coefficient of the plenum lining, α (sabins) is equal to the total lined area of the absorptive material by the random incidence absorption coefficient, q (m) is the slant distance between inlet and outlet openings and cos Ø is equal to H/q (height of the silencer over q, the slant distance).

A 50mm tontine lining was inserted on the inlet and outlet walls of the plenum chamber and the insertion loss measured.

The absorbtion coefficients for the tontine lining are given in Table 2.

Frequency (Hz)					
125	**250**	**500**	**1000**	**2000**	**4000**
0.33	0.76	0.92	0.97	1.00	1.00

.Table 2. Absrobtion coefficeints for tontine lining.

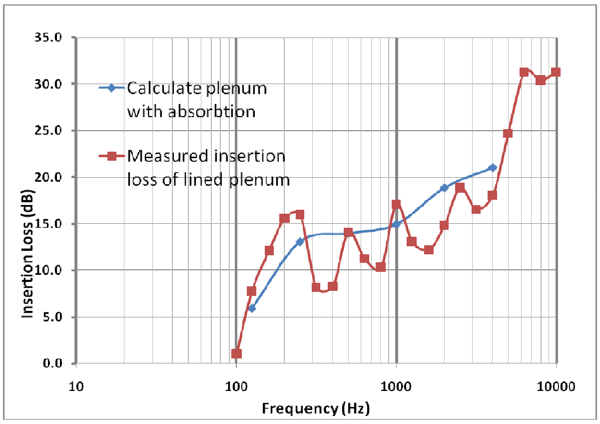

Fig.5. Measured and calculated acoustic insertion loss with 50mm tontine lining

Figure (5) shows a comparison of the calculated and measured results for the lined plenum chamber. The calculated results show the broadband attenuation which is produced when the absorptive material is added. The mesasued attenuation exhibits resonances. The trend is similar with measured and calculated results following a similar gradient. The measured spectrum shows resonances similar to those found in the unlined plenum measurements.

Figure (6) compares the measured plenum chamber attenuation with and without the tontine lining.

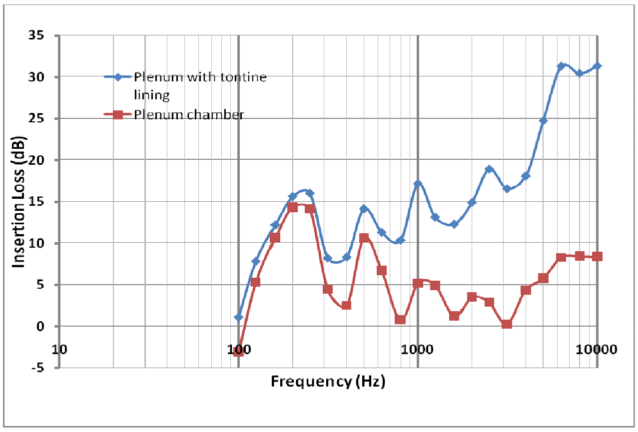

Fig. 6. Measured plenum with and without tontine lining

7. MEMBRANE EFFECT ON ACOUSTIC ATTENUATION

To test the effect of a membrane a light gauge non-porous plastic material was inserted in the plenum chamber. The material was selected as the light weight characteristics of the material were predicted to have little effect on the acoustic performance of the silencer.

Figure (7), below shows the acoustic performance with and without the membrane in place for the unlined plenum chamber.

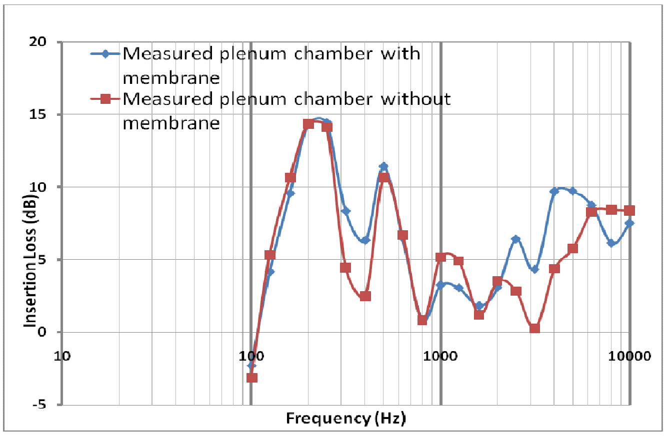

Fig. 7. Unlined plenum chamber insertion loss with and without membrane

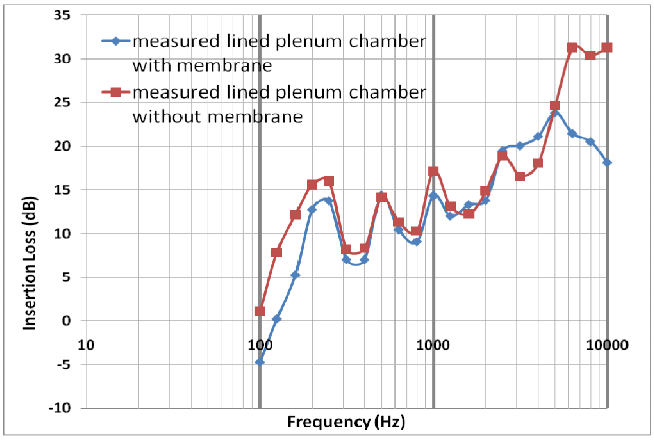

Fig. 8. Lined plenum chamber insertion loss with and without membrane.

Figure (7) shows strong correlation between the two results which suggest that membrane has little effect on the acoustic properties of the plenum chamber. This is supported in figure (8), which shows the effect the membrane has when absorptive lining is present in the silencer.

At frequencies higher than 10KHz are passed through the silencer, it is predicted that an increase in the membrane afect on the acoustic properties may be observed, as parts of the sound energy is un able to penetrate through the membrane and intern travels straight through the passage as if part of the flow.

Increasing the thickness of the material used for the membrane will also have adverse effects on the acoustic performance at high frequencies.

8. AIRFLOW TESTING

The various silencer arrangements where tested to determine the effect these had on the total pressure drop.

8.1. Computing airflow data

The total pressure loss (ΔP) was equal to the static pressure difference between the static pressure tappings in the equal area inlet and outlet ducts.

The flow was determined from the 30 point pitot traverse in the silencer inlet duct from which the average velocity (V) in the inlet duct was obtained.

From these a loss coefficient for the complete silencer was obtained as shown in equation (12)

$$K = \left(\frac{\Delta P}{\frac{1}{2}\rho V^2} \right) \tag{12}$$

8.2 Pressure drop test results

Table 3 shows value of K for the plenum chamber with and without the membrane fitted.

Description	K
Plenum Chamber	1.4
Plenum with a membrane	1.1

Table. 3. Pressure drop results with and without a membrane

The results in Table (3) show that by applying a membrane to the plenum chamber a significant decrease in pressure drop occurs

9. DISSCUSSION

The acoustic performance of plenum chambers is a well documented area of acoustics. These results show that a substantial performance increase can be gained by the inclusion of lined material. The membrane which was used for experimentation had only a small effect on the acoustic properties of the plenum chamber. Though with an increase in the mass of the membrane a more substantial effect on the acoustic performance would be anticipated.

The addition of the membrane to the plenum chamber showed a substantial reduction in pressure loss across the silencer.

10. REFERENCES

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