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THEORY AND PRACTICE IN DUCT SILENCER DESIGN

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1. INTRODUCTION

Ducts used for the distribution and transport of air and the dispersion of waste gases from boilers or gas turbines act as acoustic waveguides, particularly in the lower frequencies and silencers are required to isolate the noise generated. Silencing elements must operate in a gas stream without causing excessive local velocities, turbulence or pressure losses. The silencing mechanism must be "reactive" rather than passive, canceling or attenuating the sound while at the same time permitting the free flow of gases. Duct silencer design requires an understanding of underlying acoustic principles and a knowledge of some practical constraints.

2. MECHANISMS OF SOUND ATTENUATION

A typical dissipative duct silencer contains "splitters" that divide the duct into narrow passages with porous linings. Attenuation is a function of the passage length, relative open area and the acoustic resistivity of the lining material. Resistance to propagation of sound through the porous lining is the key mechanism of sound attenuation in a dissipative silencer. Sound pressure waves are slowed by the lining material with a phase shift that depends upon the total resistance of the material along the path of the sound waves. The waves are refracted then reflected by the duct walls to merge with the wave field in the air passage. (Adjacent passages with coherent fields behave as if a reflecting plane exists at the centerline of the splitter). Cancellation peaks at frequencies where the lining thickness is approximately $\lambda/4$ and the reflected wave is out of phase with the incident wave. For a given lining, sound attenuation is optimal at only one frequency band and performance will be shifted towards this optimum frequency.

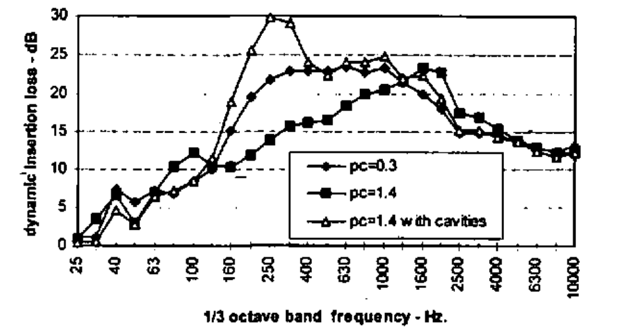
3. MATERIALS

Selecting the right liner material is critical for achieving optimum performance and service life. Acoustic materials are generally derived from thermal insulation wool products consisting of glass or mineral fibers with an organic binder. Unmodified insulation materials are widely used inlow velocity air-conditioning silencers retained by a perforated metal facing. Heavy duty industrial silencers require a more durable material to withstand aggressive operating conditions. Silencers for exhaust gases under 1,000 degrees F (538 degrees C) may use a long filament glass fiber layer beneath a permeable glass fabric to protect the acoustic core material. At higher temperatures, glass fibers are de-vitrified and lose structural rigidity. Common mineral fibers (rock-wool) will retain strength up to 1250 degrees F (677 degrees C) while some basalt fibers will retain their properties to 2000 degrees F (1093 degrees C). The flow resistance properties of a lining material are measured in the laboratory [3] with a steady state flow of between 5 and 10 feet per minute (2.5 - 5 cm/sec). Acoustic materials typically have flow resistance properties at room temperature in the range of 100 to 1,000 MKS Rayls per inch (or normalized, 0.25 to 2.5 ρc/inch) .

4. SEMI-REACTIVE SILENCERS

For low frequency noise that is dominated by discrete tones, tuned resonator chambers may be incorporated into the silencer splitters. Resonators may not be effective if located near the pressure node points of standing waves in the downstream duct and "semi-reactive" silencers with multiple locally reacting "soft" cavities in the liner have proved to be more practical for some applications. Figure 1 shows the laboratory measured dynamic insertion loss of a dissipative duct silencer with a liner thickness corresponding to a quarter wavelength at approximately 375 Hz.. The high resistance liner degrades the performance at the "tuned" frequency but improves the performance at 1600 Hz. and also at 100 Hz. This illustrates the loss that can occur when a silencer is contaminated by water or fly ash. A lining with distributed cavities (or low resistance pockets) can be shown to have characteristics of a low resistance lining plus a strong reactive contribution near the 1/4 wavelength frequency.

Figure 1. Effect of Liner Resistance



5. THE PREDICTION OF SILENCER PERFORMANCE.

The propagation of sound within a duct lined with a porous material has been studied mathematically for various limiting conditions [1]. Solutions exist for a duct with the boundary condition of a porous lining with known normal impedance (locally reacting) and the more complex condition taking into account the wave motions in the lining parallel to the duct wall (non-locally reacting). For silencers designed to operate with exhaust gases, the effects of temperature on viscosity, density and the speed of sound must also be taken into account.

Mathematical tools are invaluable for initial design studies and to optimize the choice of configurations and materials. However, for practical design, physical models are often used to predict silencer performance.

Small scale laboratory tests can project silencer performance at lower frequencies than the practical limit for measurement of a full scale model. The data can also be used to project the performance at various scale factors and operating conditions.

For accurate scaling, the total normalized flow resistance R of the model lining must equal that of the full scale lining at the design operating temperature ($R = rd/\rho c$ where r is the unit flow resistivity of the material and d is the thickness of the lining).

The characteristic impedance of the gas, ρc, is inversely proportional to the square root of its absolute temperature. Unit resistance r is proportional to the shear viscosity of air which increases with temperature roughly as $(T_1/T_0)^{0.66}$. Thus the equivalent normalized resistance properties $r/\rho c$ for a model with a scale of 1/S may be calculated thus:-

$$\left(\frac{r}{\rho c}\right)_{T0} = \left(\frac{r}{\rho c}\right)_{T1} \frac{S}{\left(\frac{T_1}{T_0}\right)^{1.16}}$$

The Dynamic Insertion Loss of small duct silencers is normally measured in the laboratory using standard procedures developed for air conditioning duct silencers [4], [5]. For scale models the procedure may be adapted as follows:-

- The model is installed in a wind tunnel at a correctly scaled location relative to the duct termination.
- The test is conducted with airflow at the full scale mach number.
- The airflow resistivity of the acoustic material is obtained for the model conditions.
- Silencer performance is measured in 1/12 octave bands.

Accurate full scale projections are made by shifting the frequencies associated with the model data so that the relationship between silencer dimensions and wavelength is maintained. The model frequencies are divided by the physical scale factor and multiplied by the ratio of the speeds of sound, cf/cm. To calculate the full scale *octave band* performance, unsilenced source levels at the critical measuring location must be considered. If the "source spectrum" is not available in 1/12 octave bands, a flat or arbitrarily sloped source must be assumed.

6. PERFORMANCE OF THE INSTALLED SILENCER

If the duct configuration is changed to accommodate the silencer, then the effect of this change on the source levels and the propagation pattern from the outlet must be accounted for. Other factors affecting installed performance are flanking, regenerated noise and contamination or erosion of the lining material.

Contamination of the induced-draft fan silencer is a serious problem in a coal fired power generating plant due to fly-ash accumulation on the acoustic material. Erosion can result from poor aerodynamic design or inadequate protection of the fibrous fill. Wrapping the acoustic material in a layer of fiberglass cloth and/or a fine wire mesh prolongs the working life of most silencers but a closely woven cloth may trap moisture or fly-ash and result in excessive liner flow resistance. Multi-layered protection has been developed for jet engine test cell exhaust silencers and other critical applications [2]. Here the approach is to use a long strand, high quality glass or mineral fiber layer to contain the acoustical material and damp out turbulent airflow.

7. CONCLUSIONS

An understanding of the basic principles of duct silencer design is essential to the writing of realistic, unambiguous specifications. Proper selection of silencer materials and a knowledge of their acoustic and structural properties under operating conditions is essential to meeting a specific performance and working life. Testing small scale models under laboratory conditions has proved to be an invaluable aid in the design and commissioning of large silencing systems.

References

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4. ASTM Standard E477. "Standard Test Method for Measuring Acoustical and Airflow Performance of Duct Liner Materials and Prefabricated Silencers".

5. BS 4718. British Standards. "Method of test for silencers for air distribution systems"