Combustion turbine silencer design, selection and applications

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While combustion turbine based power generation facilities have many noise sources, the sound emitted by the exhaust gas of a combustion turbine is often the controlling factor in a plant's audible sound and infrasound. Current exhaust systems consist of many components that inherently reduce exhaust noise including combinations of: Selective Catalytic Reduction (SCR) units, duct elbows, duct to atmosphere end reflection losses, stack top vertical directivity effects, and Heat Recovery Steam Generators (HRSG) when used in combined cycle applications. These inherent noise reduction system features, however, are usually inadequate for meeting criterion in noise critical applications and typically require additional custom engineered silencers based on parallel baffle splitter technology. While splitter based silencers are proven and effective, the exhaust system's high internal temperatures, turbulent flow, limited duct space and pressure drop requirements result in significant challenges for the silencer designer.

1 INTRODUCTION

Over the past decade and a half, evolving computer technology has enabled acoustical engineers to explore new combustion turbine parallel baffle (splitter) based silencer designs analytically, through computer codes, instead of through experimental extrapolations of previous design data. This is particularly useful since gas turbine silencers are very large, as seen in Figure 1, and costly to build. Furthermore, most gas turbine silencers are custom designed to achieve specific environmental noise criteria and are installation/location dependent.

While the computer codes provide reasonably high levels of prediction accuracy for design purposes, they also enable acoustical engineers to understand how a silencer's performance can be improved and what should be avoided. This paper addresses the aspects of combustion turbine exhaust silencer design that have major impacts on a silencer's performance and performance limitations. Discussion includes plane wave and oblique attenuation effects, baffle thickness limitations and spacing effects, offset baffle benefits, fibrous insulation effectiveness, baffle durability, and practical design limits.

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2 SILENCER INSERTION LOSS

A silencer's insertion loss is defined by the difference in sound pressure level measured at a fixed point in space before and after it is inserted within a duct. The components of silencer insertion loss include plane wave attenuation, silencer entrance losses, oblique wave attenuation and silencer exit losses. The two largest components of silencer attenuation are the plane wave attenuation and oblique attenuation.

Inserting a silencer within a duct can also modify the sound produced by the noise source itself. This effect is difficult to predict and is typically ignored in the silencer's design process.

2.1 Silencer's Least Attenuated Fundamental Mode

The least attenuated mode of sound within a duct is what typically drives the design of the silencer. The fundamental mode attenuation is normally solved for numerically, as described by Ingard [1], but simplified approximations of silencer plane wave attenuation exist, such as the Kurze approximation [2,3] shown in equation 1. The proper sign is selected to provide the least attenuation. The attenuation of the fundamental mode is linear as a function of silencer length as measured along its perforated surfaces. While lengthening a silencer will theoretically continue to increase the silencer's plane wave attenuation, seldom will an exhaust silencer's peak attenuation exceed 45-55 dB due to flanking losses and silencer self-generated flow noise.

$$\gamma = jk\sqrt{1-\left(\frac{2}{kh}\right)^2\left[1+\frac{1}{1+\frac{4Z}{jkh\rho_0 c}} \pm \sqrt{1+\frac{1}{\left(1+\frac{4Z}{jkh\rho_0 c}\right)^2}}\right]} \qquad (1)$$

where:

γ = the complex propagation constant at the fundamental (least attenuated mode) per normalized unit length.

j = $\sqrt{-1}$

k = the wave number, in 1/meter

h = the "half gap" of the silencer flow passage, in meters

ρ_0 = the density of the gas, in kg/m^3

c = the speed of sound, in m/s

Z = $R + jX$, the impedance of the silencer panel

R = Resistance portion of the impedance

X = Reactance portion of the impedance

An example of pertinent silencer geometry is provided in Figure 2.

The impedance, *Z*, is dependent on many variables including the gas density and temperature, the frequency of sound, the flow resistivity of the absorptive material (Rayls/m) and its thickness, the absorptive material's physical characteristics including its rigidity, and the presence of exterior protective facing materials [1,4,5]. Furthermore, the gas flow within the baffle passages along the silencer's perforated surface modifies the impedance of the baffle and the corresponding attenuation of the silencer. Optimizing the impedance to attain maximum silencer attenuation can generally be accomplished over a relatively narrow range of frequencies.

2.2 Oblique Wave Attenuation

When duct passage dimensions are large relative to the wavelengths attenuated by the silencer, a considerable number of higher order modes are present within the duct. In this case, the insertion loss of a silencer is typically greater than calculations based on pure plane wave attenuation. This attenuation is due to oblique wave attenuation and is applied empirically as a correction to the calculated attenuation of the fundamental mode. Generally, oblique attenuation reaches a cap, or maximum attenuation, of about 5-10 dB [6,9,11] at high-frequencies. However, measurements made in a duct with a very large cross section, 47 m^2 (500 ft^2), indicate that oblique effects may account for even larger amounts of high-frequency attenuation as shown in Figure 3. The oblique attenuation occurs within a short distance into the silencer and does not apply to attenuation of a retrofitted (extended length) silencer.

3 SILENCER PARAMETERS EFFECTING ATTENUATION

3.1 Effects of Flow on Silencer Performance

Since a gas turbine silencer is placed gas flow paths, the effects of flow need to be addressed. Flow has several components that modify a silencer's attenuation, including changing the effective propagation speed within the gas path (convective effects) and creating a velocity gradient at the baffle's surface that either focuses sound away from the silencer's surface or refracts sound toward the baffle's surface [6]. The convective effect is related to the flow speed or Mach Number (M) within the duct by a factor of 1/(1+M) [7]. M is positive when both the flow and sound are traveling in the same direction and negative when the flow and sound are traveling in opposite directions. The convective effect tends to increase the silencer's attenuation when flow is traveling opposite to the direction of sound and decrease the silencer's attenuation when sound and flow travel in the same direction. However, the velocity gradients near the baffle's surface and its modified flow resistance have a significant effect on the peak frequencies attenuated by the silencer. Figure 4 presents a comparison of estimated silencer attenuation with three flow conditions; no flow, flow and sound traveling in opposite directions, and flow/sound traveling in the same direction. When flow and sound travel in opposite directions, as is the case of an air inlet silencer, the silencer's low-frequency attenuation is improved compared to the silencer's no flow condition. However, when the sound travels in the same direction as the flow, as is the case with gas turbine exhaust, the silencer's high-frequency attenuation is improved relative to its no flow condition. This trend is somewhat disturbing for the gas turbine silencer designer since the gas turbine's exhaust has significant low-frequency content and the gas turbine's intake has significant high-frequency content.

3.2 Absorptive Fill Flow Resistivity

One of the dominant properties contributing to a silencer's performance is the flow resistivity of the baffle fill. Typical gas turbine silencer applications use basalt, mineral wool or ceramic based absorptive fills with densities in the 3.5 lbs/ft^3 to 8 lbs/ft^3 range. The material's flow resistivity, at ambient temperature, ranges from about 15,000 MKS Rayls/m to 40,000 MKS Rayls/m. Shown in Figure 5 is a comparison of attenuation measured with high flow resistivity and low flow resistivity fill materials. Both materials were measured within a full sized gas turbine exhaust duct using a loudspeaker based noise source at ambient temperature [8]. It can be seen that the low flow resistivity provides substantially better low-frequency attenuation than that of the higher flow resistivity fiber fill. However, the high-frequency attenuation of the low flow resistivity materials is significantly less than the higher flow resistivity fill provides.

While the comparisons shown in Figure 5 were based on measurements taken in a cold duct, the silencer's performance at operating temperature would be different. The flow resistivity scales with temperature and increases by approximately the ratio of the absolute temperatures, $(T_{operational}/T_{ambient})^{1.65}$ [5]. In the case of a gas turbine exhaust silencer where the exhaust temperature is often greater than 550 ^{o}C, the effect is significant. Care should be taken when measuring an exhaust silencer's noise reduction in an ambient temperature duct. The attenuation will not simply scale as a function of wavelength at the higher temperature.

3.3 Soft Versus Rigid Baffle Fibrous Fill (Insulation) Materials

Theoretical and empirically based impedance models exist [1,4,5] for two basic types of absorptive materials:

1.) impedance models based on rigid frame materials,
2.) impedance models based on softer limp-blanket or cotton-like materials.

The use of either rigid frame or limp blanket impedance models generally result in similar predicted attenuation across the silencer's mid- and high-frequency range. However, the structural compliance of the softer flexible materials tends to improve the predicted low-frequency attenuation of the silencer. The attenuation of the flexible absorber can be manipulated, to some extent, to exploit the absorptive properties within a desired range of low-frequencies by altering the fill's contact with protective materials such as fine mesh screens or other perforated facing materials. The beneficial effects related to the softer limp-blanket materials are lost, however, in applications that are built with the material under substantial compression within the baffle frame, or silencers that have been in operation for extended periods due to material settling or natural compression. In real gas turbine field applications, the silencer insulation appears to act more rigid than flexible. In general, the low-frequency performance of a gas turbine silencer rarely performs as well as a pure flexible impedance model would predict but slightly better than pure rigid frame impedance models predict.

3.4 Silencer Protective Facings

To protect the fibrous fill from the turbulent flow of a gas turbine's exhaust, the silencer's baffles are constructed with sound transparent protective surfaces such as perforated plate, fine wire mesh stainless steel screens and needle mat [1,10]. Typical perforated plate open areas range from 15% to 33%. Fine mesh screens (20x20 to 40x40) are less than 25 MKS Rayls and needle mats are typically 300-700 MKS Rayls at ambient temperature.

In general, it is desirable to design the protective facings to be "transparent" the sound. However, facings can be used to enhance some frequency ranges. Shown in Figure 6 is the comparison of silencer attenuation observed with a high flow resistivity (3000 MKS Rayls) and moderate flow resistivity (1000 MKS Rayls) protective fiberglass cloth. The high flow resistivity cloth significantly reduces the silencer's mid-frequency performance. However, the very low- and very high-frequencies are somewhat improved by the higher flow resistivity cloth.

3.5 Baffle Thickness

Reducing low-frequency rumble or infrasound is often a requirement in simple cycle gas turbine based power plants. The gas turbine's low-frequency noise is predominantly generated by the gas turbine's exhaust. Often very thick baffles are proposed to reduce the low-frequency sound. However, the flow resistance of the fill material limits the depth sound can penetrate into the baffle. Shown in Figure 7 is the estimated performance of four different baffle thicknesses ranging from 15 inches to 30 inches thick for a 15,000 MKS Rayls/m flow resistivity fill. The trend shows that a small amount of additional attenuation can be obtained at low-frequencies by moving toward thicker silencer baffles but the mid- and upper-frequency sound shows no appreciable improvement. Furthermore, the minor improvement that does occur at low-frequencies comes at the expense of losing available open duct flow area. Restricted flow areas result in higher flow velocities, higher self-generated noise and larger pressure drops. Assuming the silencer is designed to reduce the fundamental mode, designs based on filling the available duct space with thinner baffles spaced closer together can theoretically be made to attenuate the low-frequency sound equally well for a given available length (L) of duct. Under most situations, the best attainable plane wave attenuation in the critical 16 Hertz, 31.5 Hertz and 63 Hertz octave bands is less than (L * 0.2 dB/2h), (L * 0.3 dB/2h) and (L * 0.4 dB/2h), respectively, where L is the silencer length and 2h is a full baffle gas flow passage width.

3.6 Offset Baffles

Offsetting a silencer's baffles is often considered to improve its performance. Short wavelengths, relative to a silencer's gas passage width, result in the high-frequency sound beaming through the flow passages [6]. Offsetting the baffles to block the line of sight can improve the high-frequency attenuation as illustrated in Figure 8. The offset design, however, is only effective in reducing high-frequency sound and is most appropriately used for relatively short silencers or silencers with very open gas paths. The maximum high-frequency attenuation is typically about 10 dB and no appreciable sound level reduction is observed at lower frequencies.

4 SILENCER LIFE, INSULATION LOSS AND SETTLING

When gas turbine exhaust silencers are examined after many years of operation, there is often a loss of the internal insulation accompanied by some loss of the silencer's effectiveness. The loss of a silencer's baffle fill can be due to the partial breakdown of the fibers from years of thermal cycling, simple flow erosion and mechanical vibration. To greater or lesser degrees, baffle fill loss and/or settling is seen in nearly all gas turbine exhaust silencers. However, minor losses of insulation typically result in relatively minor degradations of silencer performance.

4.1 Silencer Fill Settling

In loosely packed silencers, the insulation settles in the baffle frame over time due to gravity, vibration and thermal cycling. The settling and corresponding compacting of the insulation tends to increase the fill density toward the lower elevations of the baffle while leaving empty pockets or gaps at the top of the baffle frames. The compressed baffle fill results in a higher flow resistivity material and slightly reduced attenuation in the silencer's mid-frequency range.

4.2 Baffle Fill Erosion

The turbulent flow of the gas turbine's exhaust can quickly erode the baffle's fill if the silencer is located too close to the gas turbine exhaust or if poor flow characteristics exist in the ducting. In many cases, baffles are found completely void of insulation after just a few years of operation. Curiously, the loss of silencer performance is typically small and usually not noticed by plant owners or neighbors.

5 SUMMARY

Several parameters associated with gas turbine silencer design have been addressed relating to its design and life.

Driving a silencer's design is the attenuation of the each frequency's fundamental mode. The fundamental mode attenuation is directly related to the silencer's normalized length [length / (gas path spacing)]. The attenuation is further influenced by gas path flow speed and direction, temperature, and the baffle's absorptive fill and protective surface flow resistivity. Baffle thickness also has a moderate effect on reducing low-frequency sound but has little impact on mid- and high-frequency sound. However, increased baffle thickness results in smaller open areas within the available duct space and must be weighed against pressure drop criteria and potentially higher self-generated flow noise.

Offsetting baffles such that the line of sight is broken through the silencer can be an effective way of reducing high-frequency sound – particularly in limited length silencers. However, when wavelengths are large relative to the gas path width, little sound attenuation is observed by offsetting the baffles.

Over the life of the gas turbine exhaust silencer, most will lose absorptive fill due to flow erosion and insulation settling. In many cases, the baffle fill loss will likely create empty cavities within the silencer baffle frames. The reduced attenuation of the deteriorated silencer, however, is seldom noticed by plant personnel or neighbors.

6 REFERENCES

1. Uno Ingard, *Notes on Sound Absorption Technology*, Noise Control Foundation, Poughkeepsie, New York (1994).
2. Kurze, "Schallausbreitung im Kanal mit periodischer Wandstruktur", *Acustica*., 21(2), 74-85, (1969).
3. Theodore J. Shultz, "Wrappings, Enclosures and Duct Linings", Chap. 15 in *Noise and Vibration Control,* edited by Leo L. Beranek, *revised edition* Institute of Noise Control Engineering, (1988).
4. Allard and Champoux, "New empirical equations for sound propagation in rigid frame fibrous materials", *J. Acoust. Soc. Am.,* **91**(6), 3346-3353, (1992).
5. Fridolin P. Mechel and Istvan L. Ver, "Sound Absorbing Materials", Chap. 8 in *Noise and Vibration Control Engineering-Principles and Applications,* edited by Leo L. Beranek and Istvan L. Ver, Wiley, New York, (1992).
6. Anthony G. Galaitsis and Istvan L. Ver, "Passive silencers and lined ducts", Chap. 10 in *Noise and Vibration Control Engineering-Principles and Applications,* edited by Leo L. Beranek and Istvan L. Ver, Wiley, New York, (1992).
7. T. F. W. Embleton, "Mufflers", Chap. 12 in *Noise and Vibration Control,* edited by Leo L. Beranek, *revised edition* Institute of Noise Control Engineering, (1988).
8. David J. Parzych and Stanley A. Youtt, "*An Experimental Investigation Of Combustion Turbine Exhaust Stack Silencer Performance"*, Proc. NOISE-CON 1998, Ypsilanti, Michigan, (Noise Control Foundation, Poughkeepsie, New York, 1998).
9. Harold W. Lord, William S. Gatley, Harold A Eversen, "Acoustical Materials and Structures", Chap. 8 in *Noise Control for Engineers*, McGraw-Hill, New York, (1980).
10. Leo L. Beranek, "Acoustical Elements", Chap. 5 in *Acoustics,* American Institute of Physics, New York (1986).
11. Doelling, N., "Dissipative Mufflers", Chap. 17 in *Noise Reduction*, edited by Leo L. Beranek McGraw-Hill, New York, (1960).

Fig. 1 – Installation of a horizontal gas turbine exhaust silencer

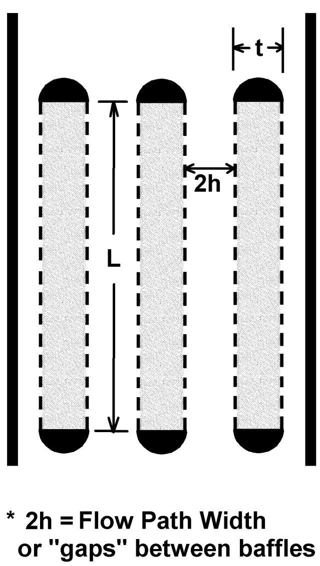

Fig. 2 – Silencer geometry.

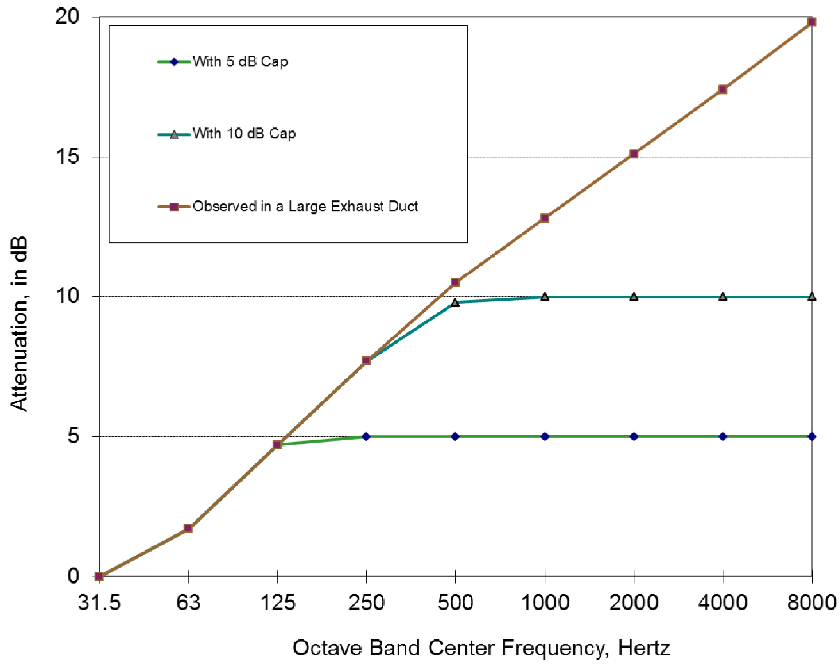

Fig. 3 – Oblique wave losses observed in a large exhaust duct.

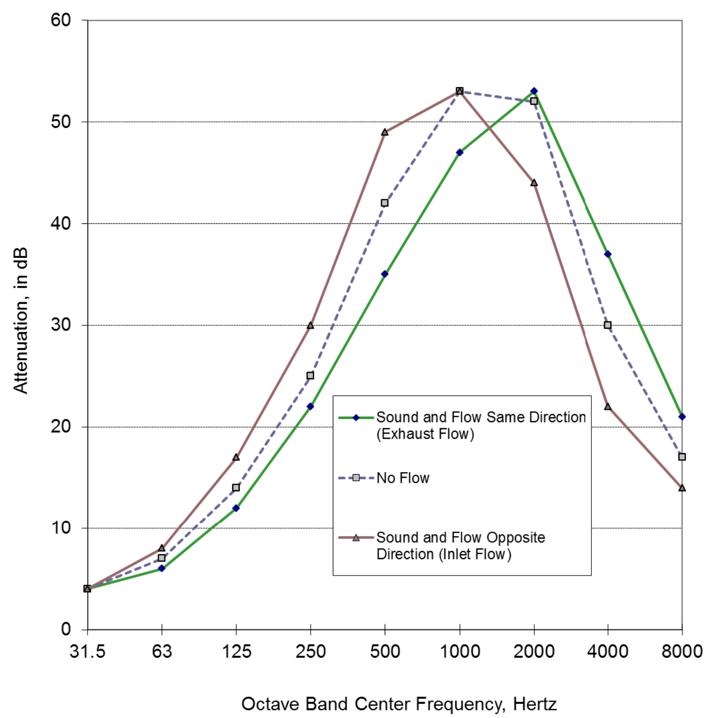

Fig. 4 – Silencer passage velocity effect

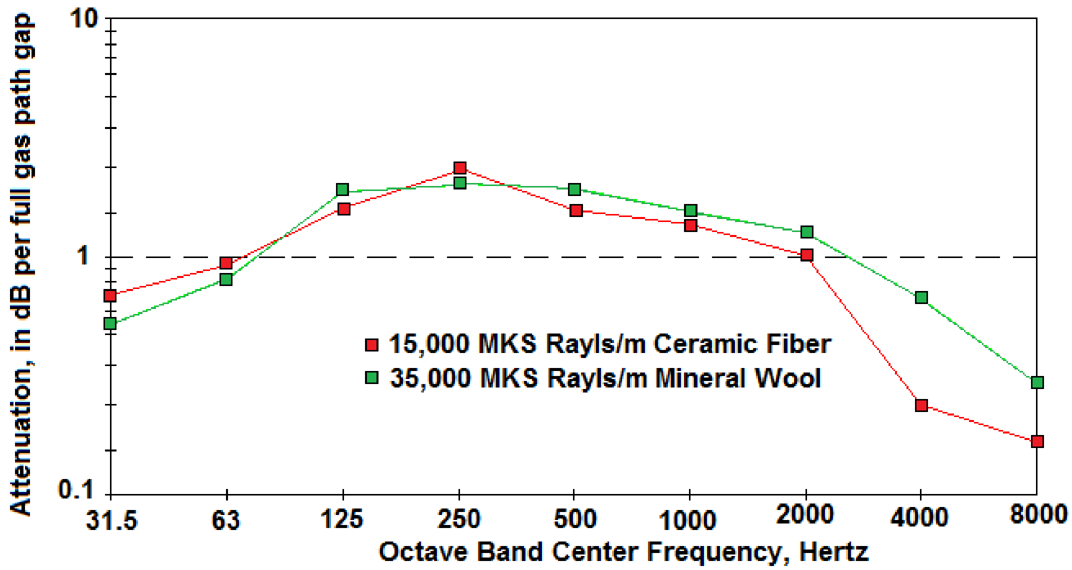

Fig. 5 – Measured silencer attenuation for two baffle fill materials in a cold duct

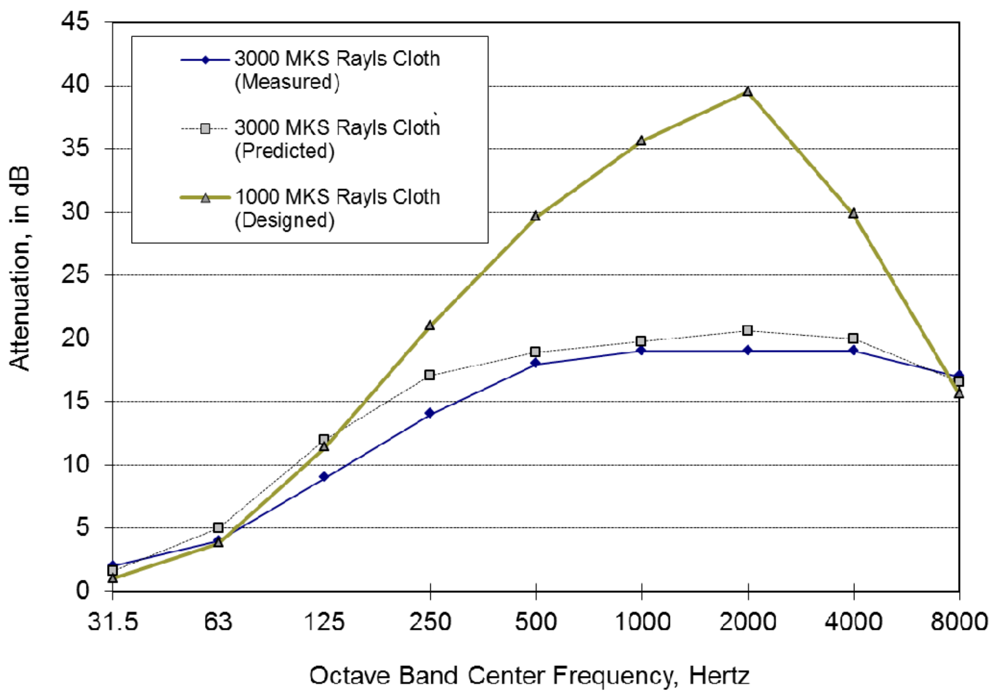

Fig. 6 – Effect of baffle protective facing on a cold duct silencer

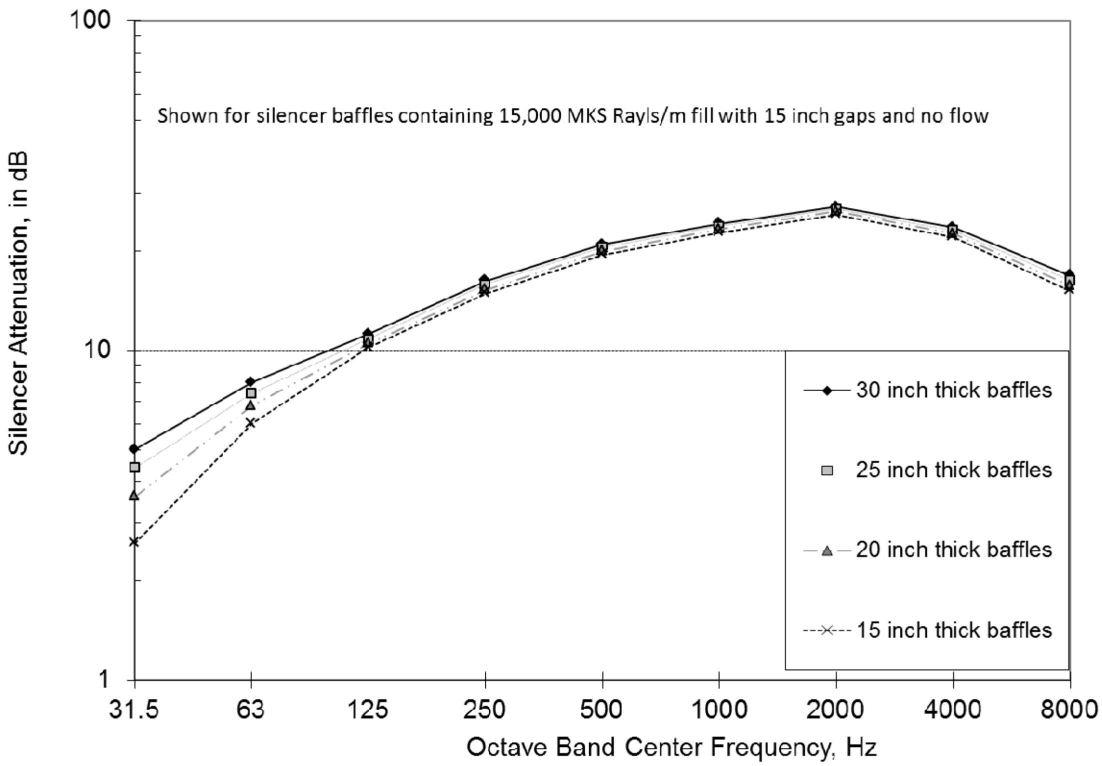

Fig. 7 – Predicted silencer attenuation for various baffle thickness in a hot duct

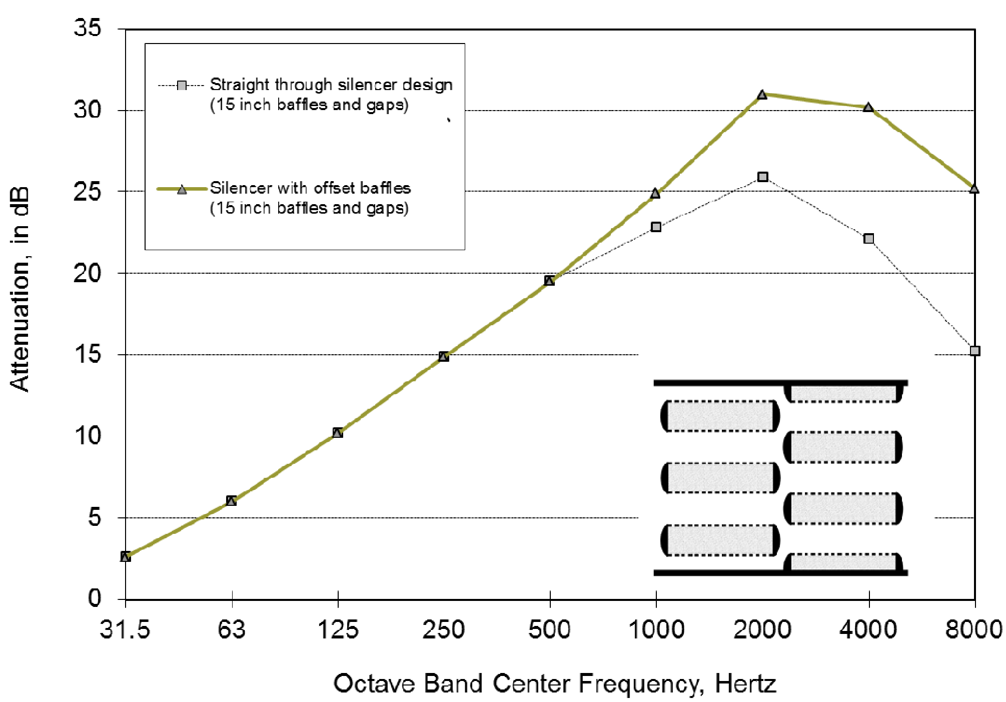

Fig. 8 – Effect of offset baffle centerlines