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Sound Attenuation for HVAC Ducts Using Porous Absorbers of Different Sound Absorption Coefficient

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***Abstract* - Sound attenuation is done by active sound attenuator or by passive sound attenuator. In case of active sound attenuation the anti-noise source is used to reduce the intensity of noise however, in passive sound attenuation various types of sound absorbing porous materials are used to absorb sound energy. In passive sound attenuators the substantial portion of the mechanical pressure wave penetrates to the pores before encountering to the solid surface. Large number of interactions takes place and the energy is transferred to the solid structure through the frictional losses and the sound intensity is reduced. Passive sound attenuator is used in Heating Ventilation and Air Conditioning (HVAC) duct to reduce the sound produced by the blower. Two porous materials of different sound absorbing coefficients are used in the attenuator. This passive attenuator is specifically designed to study the effect at low sound frequency. Frequency of sound is measured with the help of Lab VIEW software. Intensity of sound is measured using digital decibel (dB) meter. To measure the pressure drop digital anemometer is used. Along with the combination of porous materials the effect of thickness of porous absorber and the angle of porous absorbers with the direction of air stream is studied.**

***Keywords* - Sound Absorption Coefficient, Porous Materials, Low Frequency sound, blade pass frequency, HVAC sound attenuation and pressure drop.**

I. INTRODUCTION

Sound is an audible mechanical pressure wave which travels through media like air, water and solid. Sound attenuation is nothing but the reduction of intensity of sound by using Active sound attenuation or Passive sound attenuation. In case of Heating Ventilation and Air-Conditioning (HVAC) the ducts carry the conditioned air from Air Handling Unit (AHU) to the space to be heat, ventilate or cooled. Blower is responsible for the movement of air from AHU to the space and back from space to AHU. While doing so the noise created at the blower is getting carried with the conditioned air to the space. Hence, it is necessary to attenuate this sound by using one of the methods of Active or Passive attenuation.

Active sound attenuation is achieved by using the anti-noise source in the HVAC duct, which creates the sound wave opposite to the sound wave created by the blower. Various types of secondary speakers are used to create the anti-noise. These are having high sound absorption coefficient at low frequencies [1], [2].

Passive sound attenuation is achieved by using the porous sound absorbing materials. Common porous absorbers include carpet, draperies, spray-applied cellulose, aerated plaster, fibrous mineral wool and glass fiber, open-cell foam, and felted or cast porous ceiling tile. Generally, all of these materials allow air to flow into a cellular structure where sound energy is converted to heat. Thickness plays an important role in sound absorption by porous materials. These attenuators are suitable basically for the high frequencies. However, the study of this paper is with passive attenuation at low frequencies.

II. SOURCES OF SOUND IN HVAC

When the Air handling Unit switched on the blower starts pumping air to the ducts. While pumping the air to the duct the vibrations of the blower are transferred along with the air. The audible pressure waves are created because of these vibrations which are responsible for the noise and transferred to the rooms along with the air.

Following are the basic causes of noise in air circulating blower:

- Blade thickness noise
- Non Uniform inlet flow
- Rotor Casing Interaction
- Rotating Stall
- Non Uniform Rotor Geometry
- Unsteady Flow Field
- Tip Vortex

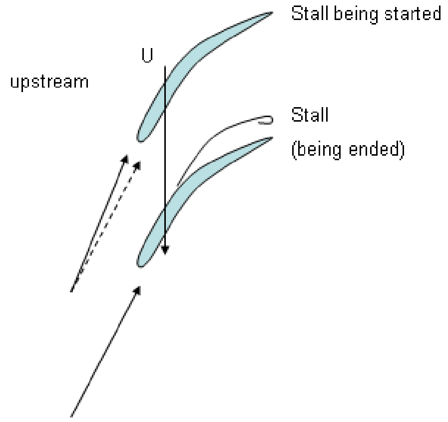
1. Blade thickness noise

Blade thickness noise is generated by volume displacement of fluid. Fan blade has its thickness and volume. As the rotor rotates, the volume of each blade displaces fluid volume, then they consequently fluctuates pressure of near field, and noise is generated. This noise is tonal at the running frequency and generally very weak for low speed fans.

2. **Non Uniform inlet flow**
Non-uniform (still steady) inlet flow causes non-uniform aerodynamic forces on blades as their angular positions change. This generates noise at blade passing frequency and its harmonics. It is one of the major sources of noise.

3. **Rotor Casing Interaction**
If the fan blades are very close to a structure which is not symmetric, unsteady interaction forces to blades are generated. Then the fan experiences a similar running condition as lying in non-uniform flow field.

4. **Rotating Stall**
In stall condition the angle of attack increase beyond certain point such that the lift begins to decrease. The angle at which this occurs is called as the critical angle of attack. The noise due to stall is a complex phenomenon that occurs at low flow rates. For some reason, if flow is locally disturbed, it can cause stall on one of the blades. As a result, the upstream passage on this blade is partially blocked. Therefore, the mean flow is diverted away from this passage. This causes increasing of the angle of attack on the closest blade at the upstream side of the originally stalled blade, the flow is again stalled there. On the other hand, the other side of the first blade is un-stalled because of reduction of flow angle.



Repeatedly, the stall cell turns around the blades at about 30~50% of the running frequency and the direction is opposite to the blades. This series of phenomenon causes unsteady blade forces, and consequently generates noise and vibrations.

5. **Non Uniform Rotor Geometry**
Asymmetry of rotor causes noise at the rotating frequency and its harmonics, even when the inlet flow is uniform and steady

6. **Unsteady Flow Field**
Unsteady flow causes random forces on the blades. It spreads the discrete spectrum noises and makes them continuous. In case of low-frequency variation, the spread continuous spectral noise is around rotating frequency, and noise is generated.

7. **Tip Vortex**
Since some cooling fans are ducted axial flow machines, the annular gap between the blade tips and the casing is important parameter for noise generation. While rotating, there is another flow through the annular gap due to pressure difference between upstream and downstream of fan. Because of this flow, tip vortex is generated through the gap, and noise increases as the annular gap gets bigger.

III. PROPAGATION OF SOUND WAVE

The behavior of sound propagation is generally affected by three things:

- A relationship between density and pressure. This relationship, affected by temperature, determines the speed of sound within the medium.
- The propagation is also affected by the motion of the medium itself. For example, sound moving through wind. Independent of the motion of sound through the medium, if the medium is moving, the sound is further transported.
- The viscosity of the medium also affects the motion of sound waves. It determines the rate at which sound is attenuated. For many media, such as air or water, attenuation due to viscosity is negligible.

Speed of Sound

Speed of sound depends on two factors:

- Elastic Property
- Inertial Property

Elastic Property

Elastic properties are those properties related to the tendency of material to maintain its size and shape and do not deform when force is applied. Steel is considered to be stiff with high elasticity. On the other hand rubber band is highly flexible which deforms and changes its shape when force is applied.

At particle level a stiff or rigid material is characterized by atoms and/or molecules with strong attraction for each other. Hence when force is applied is an attempt to stretch or deform the material, its strong particle interaction prevent this deformation and help the material to maintain its shape. As there is strong interaction between particles in case of solid the longitudinal sound wave travels faster than liquid and gases.

$$\text{i.e. } V_{solid} > V_{liquid} > V_{gases}$$

Inertia Property

These properties are related to the material tendency to be sluggish to change in its state of motion. The density is one of the inertia properties. The greater the inertia (i.e. mass density) of individual particles of the medium, the less responsive they will be to the interaction between neighboring particles and slower that the wave will be i.e. sound wave will travel faster in less denser material than more denser material.

Instead of Inertia properties the elastic properties have high influence on the speed of sound. The speed of sound (V) is given by

$$V = \sqrt{\frac{C_{ij}}{\rho}}$$

Where, C_{ij} is bulk density and ρ is density of medium.

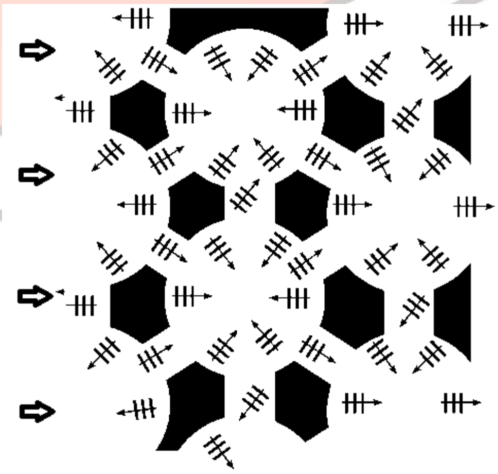
Effect of temperature on speed of sound

Speed of sound increases with increase in temperature. Heat is a form of Kinetic Energy. Molecules will have more energy at high temperature, thus they can vibrate faster. Since the molecules vibrate faster, sound wave can travel faster. Speed of sound is given by,

$$V = \sqrt{\gamma RT}$$

Absorption of sound wave in porous media [4]

Acoustic energy can be converted into heat through a number of mechanisms. Viscous stresses caused by shearing of the fluid convert fluid kinetic energy into heat. This heat can be transferred from fluid into a solid structure through heat conduction. Impact of an acoustic pressure wave on a solid structure can dissipate energy through flexing of the solid frame. If the solid surface is non porous, incident energy reflects back into environment and lost. However, if that surface is highly porous, a substantial portion of pressure wave penetrates the material before encountering a solid surface. The same efficient reflections occur but are structure where the chances are great that the reflected energy will encounter another part of the solid structure before being lost to the environment. A high number of internal reflections occur and can transfer energy to the solid structure through frictional losses and efficiently absorb sound



Highly porous materials are not suitable for acoustic absorption. If the mean free path of air is on the order of that of mean distance between pore walls, pressure wave will not be able to efficiently penetrate the material.

Sound Attenuator with combination of porous materials

Combination of two porous materials with different sound absorbing coefficient is used to study the effect on the overall sound absorption at low sound frequencies. Total six numbers of porous absorbers are used, three of each material and have different thickness for both the absorbers. The average thickness of absorbers is maintained to be 50 mm. The angle is given to the porous absorber with respect to air stream to study the effect on the sound absorption coefficient. The porous materials used are Elastomeric Foam and Glass Wool. The LabVIEW software is used to measure the frequency of sound. Microphone is used to measure sound which is connected to card 9234. This card is interfaced with the computer. The intensity of sound is measured with the help of digital decibel (dB) meter. Sound absorption coefficient is calculated with the help of intensity of sound at inlet and outlet and given by,

$$\alpha = \frac{I_i - I_o}{I_i}$$

Where, α sound absorption coefficient,
I_i Intensity of sound at inlet,
I_o Intensity of sound at outlet.

Pressure drop across the attenuator is also calculated. To calculate the pressure drop digital anemometer is used which measures the velocity at inlet and exit of sound attenuator. Hence, by using Bernoulli's equation the pressure drop is calculated.

Blade-Pass Frequency [4]

Blade passage frequency can be perceived as a tone. All fans generate a tone at this frequency and its multiple (harmonics). Whether this tone is objectionable or barely noticeable is depends on the type and design of the fan and the fan operation.
Blade-Pass Frequency is given by,

$$B_f = \frac{n \times t}{60} Hz$$

Where, B_f is blade − pass frequency
n is speed of blower in revolution per minute,
t is number of blades

Backward inclined, Airofoil and Axial flow fans are louder at the blade pass frequency where as the forward curved fans are less prominent at blade-pass frequency at having sound higher at high frequencies.

IV. Experimental Results

To determine the effect of combination of material on the sound absorption coefficient two parameters are selected. These are thickness of porous absorber and the angle of porous absorber with air stream. When the thickness is considered three levels for the thickness are taken in which three different thicknesses of Elastomeric Foam and Glass wool are considered. At level 1 the thickness of Elastomeric Foam is considered to be 25 mm and that for the Glass Wool it is 75 mm. Similarly at level 2, 50 mm thick for Elastomeric Foam and 50 mm thick for glass wool is considered and at level 3, 75 mm thick of Elastomeric Foam and 25 mm thick of Glass Wool is considered. For the other parameter i.e. angle of absorber with air stream again three levels are considered. At level 1 the angle considered is 0˚, at level 2, 2˚ and at level 3 it is taken as 4˚. Hence, the experiment is performed with two factors at three levels. Applying the Design of Experiments the L9 orthogonal array is selected and as per this orthogonal array all 9 experiments are performed at various levels where, experiments are based on full factorial design.

To analyse the results Analysis of Variance (ANOVA) table is used. Along with this the response table for means at various levels of factors is prepared to determine in which order the each factor is contributing to the response. Percent contribution is also found out to determine the percentage of contribution of each factor towards response.

Material Combination: Elastomeric Foam and Glass Wool				
Thickness of porous absorbers (mm)	**Angle of porous absorbers (deg)**	**Intensity of sound before sound attenuator (dB)**	**Intensity of sound after sound attenuator (dB)**	**Sound Absorbing Coefficient**
25-75	0	90.4	76.91	0.1496
25-75	2	90.4	76.37	0.1556
25-75	4	90.4	76.94	0.1492
50-50	0	90.4	77.21	0.1462
50-50	2	90.4	77.01	0.1484
50-50	4	90.4	77.69	0.1410
Material Combination: Elastomeric Foam and Glass Wool				
Thickness of porous absorbers (mm)	**Angle of porous absorbers (deg)**	**Intensity of sound before sound attenuator (dB)**	**Intensity of sound after sound attenuator (dB)**	**Sound Absorbing Coefficient**
75-25	0	90.4	76.83	0.1505
75-25	2	90.4	76.23	0.1571
75-25	4	90.4	76.36	0.1557

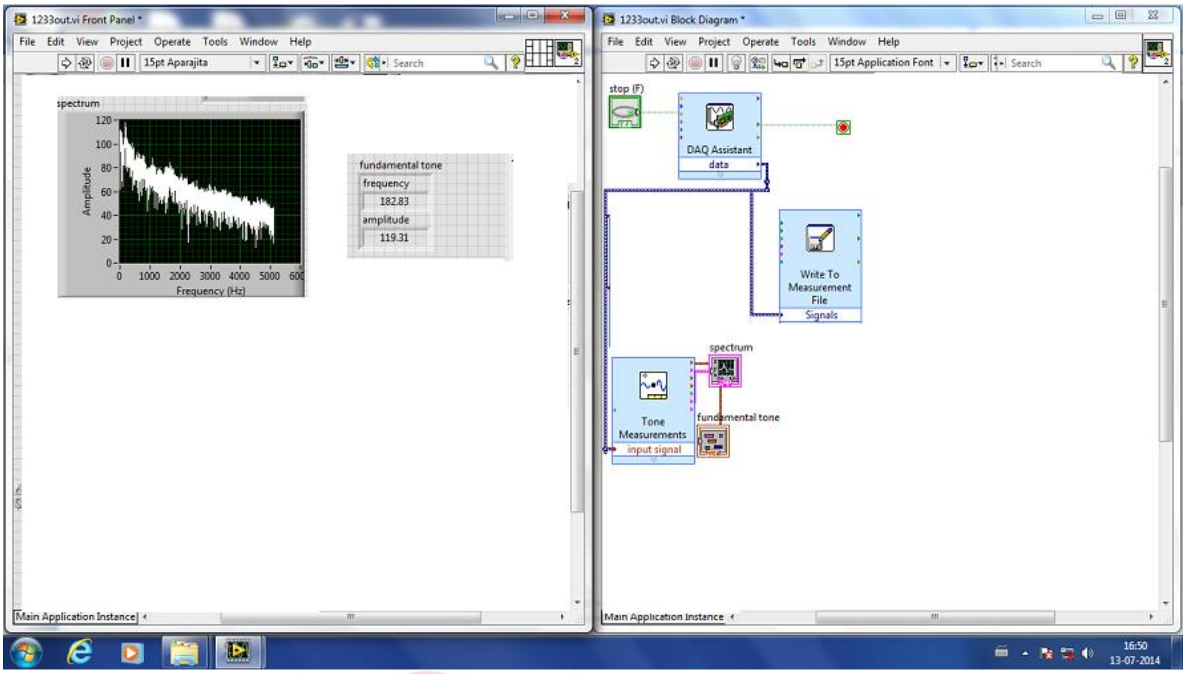
Theoretical frequency of sound

The blower used for the experimentation is of Airofoil type and hence it is having the maximum sound at blade-pass frequency. The blower having the 1440 revolutions per minute and have 12 numbers of blade. Hence, the frequency of sound is given by using equation

Therefore, the theoretical frequency of sound is 288 Hz.

Experimental frequency of sound

To find frequency of sound experimentally the LabVIEW software is used. The result of which is shown in fig.



From the fig. it is seen that the experimental frequency of sound measured is about 183 Hz. From the amplitude verses frequency plot it is seen that the maximum amplitude is at the frequency about 183 Hz.

As the actual frequency is below 250 Hz, it is said to be low frequency. This frequency lies in the 125 Hz centre frequency of octave band whose range is from 88 Hz to 177 Hz. However, the actual frequency of sound is very nearer to this range so it is considered in the 125 Hz center frequency band.

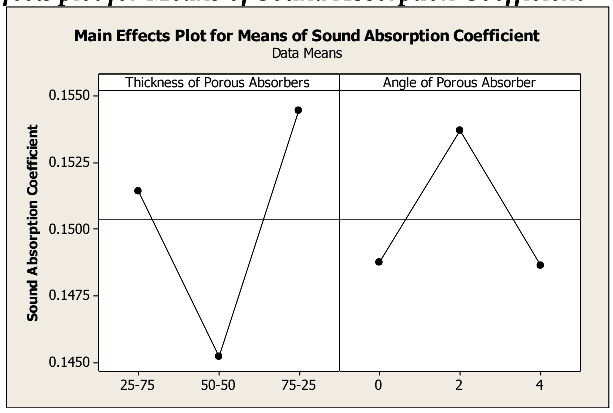
V. ANALYSIS OF EXPERIMENTAL RESULTS:

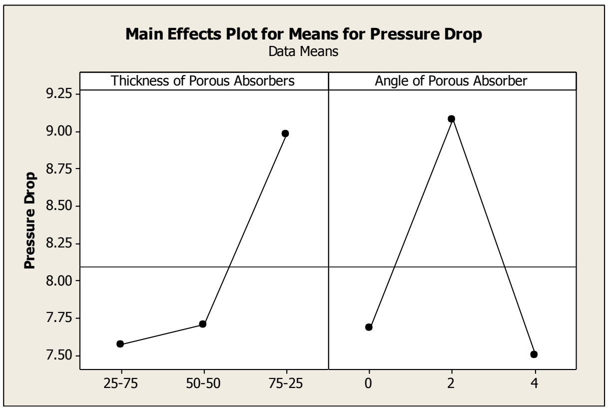
Response table of mean for sound absorption coefficient

Column	Factors	Level 1	Level 2	Level 3	Delta	Rank
1	Thickness of Porous Absorber	0.1515	0.1452	0.1545	0.00923	1
2	Angle of Porous Absorber	0.1488	0.1537	0.1487	0.0051	2

From the response table of mean of sound absorption coefficient it is seen that the highest rank is for thickness of porous absorber and hence, the thickness of porous absorber is having higher effect on the sound absorption than the angle of porous absorber i.e. the thickness of porous absorber is significant factor compared to the angle of porous absorber.

Main effects plot for Means of Sound Absorption Coefficient





From the fig. for plot of Means of sound absorption coefficient, it is seen that for the third level of thickness i.e. 75 mm thickness of Elastomeric Foam and 25 mm thickness of Glass Wool and second level of angle i.e. 2° angle of the porous absorber the sound absorption coefficient is high.

Main effects plot for Means of Pressure Drop

From the fig. for plot of Means of pressure drop, it is seen that for the third level of thickness i.e. 75 mm thickness of Elastomeric Foam and 25 mm thickness of Glass Wool and second level of angle i.e. 2° angle of the porous absorber the pressure drop is high

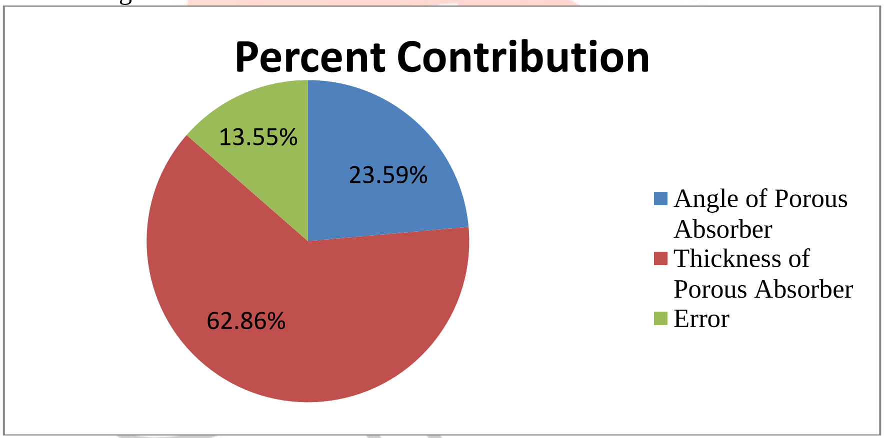
Analysis of Variance (ANOVA) Table

Factors	Sum of Squares	Degrees of Freedom	Mean Square	F_0	F_{table} at 95%	Percent Contribution
Thickness of Porous Absorbers	0.000133	2	6.67E-05	9.275	6.94	62.86
Angle of Porous Absorbers	5.0026E-05	2	2.501E-05	3.481	6.94	23.58
Error	2.875E-05	4	7.186E-06			13.55
Total	0.0002121					

From the ANOVA table, table, it is seen that the thickness of porous absorber factor is most significant than the angle of porous absorber. The F_{table} values are taken at 95% confidence level with respect to 2 degrees of freedom in numerator for both factors and 4 degrees of freedom in denominator for the error.

Percent Contribution

Percent contribution is also used to determine the significant factor. It is a function of sum of squares. This is calculated by taking the ration of sum of squares of each factor with respect to the sum of squares of total. From the ANOVA table given in table it is seen that the thickness of porous absorber is having the highest contribution towards response as compared to angle of porous absorber and error. Error is having the lowest contribution which indicates that no significant factor is missed. Hence, the thickness of porous absorber is a significant factor.



VI. Conclusion

This paper has attempted to lay the general sources of sounds in HVAC systems. Study includes the passive attenuation at low sound frequencies. Sound absorption coefficient is determined at low frequencies by using two different porous absorbers which have different sound absorbing coefficients. Factors affecting the propagation of sound wave and the speed of sound wave are studied. Paper has given attempt to the general mechanism of sound absorption in the porous materials. This paper also includes the general idea about the blower loudness at various frequencies i.e. at low frequency, high frequency or at blade-pass frequency.

From the experimental result and analysis it is seen that the combination of Elastomeric Foam & Glass Wool has a high sound absorption coefficient at 75 mm thickness of Elastomeric Foam and 25 mm thickness of Glass Wool and an angle of 2°. The thickness of sound absorbers is significant factor for the porous absorption as compared to the angle of porous absorbers. Thickness of porous absorbers has highest contribution towards the response.

VII. References

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