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Design Principles and Optimization of Exaust Reactive Muffler

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ABSTRACT

Engine exhaust noise pollutes the street environment and ventilation fan noise enters dwellings along with the fresh air. Work on the analysis and design of mufflers for both these applications has been going on since the early 1920.The exhaust system being the primary source of engine noise(combustion-induced structural vibration sound is the next in importance for diesel engines).

In our modern, rapidly expanding environment one of the developing problems is that of "Noise". In diesel engine the pollutant is exhaust noise. In the analysis of C.I. Engine noise the maximum sound pressure level comes out at exhaust and the acoustic power increases as load increases for all compression ratios. However this noise can be reduced sufficiently by means of a well designed muffler. The suitable design and development of muffler will help to reduce the noise level but at the same time the performance of engine should not be hampered due to back pressure created by muffler.

This paper discusses the design principles and optimization of reactive mufflers. While designing a muffler for any applications there are several functional requirements that should be considered, which includes both acoustic and non-acoustical design issues as detailed in this paper

Keywords— ***Muffler, Back Pressure, insertion loss, Engine performance Design***

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I. INTRODUCTION

Mufflers are components of an automobile's exhaust system that helps in the drop of noise produced when exhaust gases leave the engine. Mufflers are usually installed at the end of exhaust pipes which are parts of an exhaust system. Mufflers are created and designed with resonating chambers that reduce noise created by gases flowing out of the exhaust system. Mufflers are coated with different anti corrosion solvents or materials that help prevent rusts and other corrosions Mufflers have various chambers and holes created and mounted inside them. These chambers are refrained to reduce and eliminate noise created by exhaust gases. These muffler chambers are designed to reflect sound waves produced by engines. Exhaust gases and sound waves enter the muffler and bounce off from the chamber of the muffler; they pass through different holes created inside the muffler before exiting the tailpipe and leaving the muffler.

II. MUFFLERS

Mufflers are typically classified as either resistive or reactive. Resistive devices primarily utilize energy dissipation to provide their attenuation. Reactive devices primarily utilize impedance changes to reflect acoustic energy back to the source to provide a stated transmission loss. In reality all reactive silencers do produce some resistive attenuation as the sound passes through various openings, perforations and tubes within the silencing element. Resistive mufflers create less back pressure than reactive but they do not reduce sound well [1]. So reactive mufflers more used in automobile to reduce noise specifically in passenger cars.

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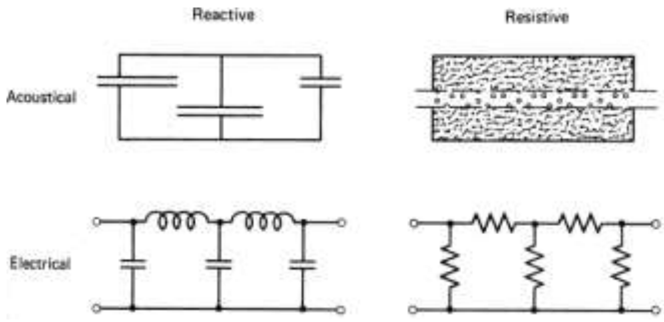


Fig 1:- Comparison of reactive and resistive filters using acoustical and electrical examples.

As shown in figure 1, reactive acoustical silencers utilize various combinations of tubes and chambers to maximize attenuation over a broad frequency range. They are analogous to an electrical low-pass filter made up of a series-parallel arrangement of inductors and capacitors. Resistive acoustical silencers utilize various arrangements of sound absorptive material for similar results. They are analogous to an electrical attenuator made up of electrical resistors.

In Resistive muffler (fig. 2) uses sound absorbing material to take energy out of the acoustic motion in the wave, as it propagates through the muffler. It is composed of a tube covered by sound absorbing material. The tube is perforated so that some part of the sound wave goes through the perforation to the absorbing material. The absorbing material is usually made of fiberglass or steel wool. The sound absorbing material used in silencer converts acoustic waves into heat and that heat radiated from silencer.

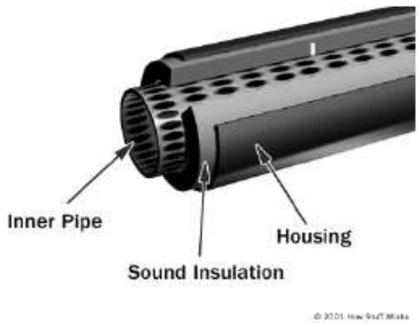


Fig 2:-Resistive muffler

Reactive muffler reflects the sound waves back towards the source and prevent sound from being transmitted along the pipe. Reactive silencer design is based either on the principle of a Helmholtz resonator or an expansion chamber.

Inside the reactive muffler of expansion chamber type (fig. 3) is a set of tubes. These tubes are designed to create reflected waves that get in the way with each other or cancel each other out. The exhaust gases and the sound waves enter through the center tube. They bounce off the back wall of the muffler and are reflected through a hole into the main body of the muffler. They pass through a set of holes into another chamber, where they turn and go out the last pipe and leave the muffler.

A chamber called a resonator is connected to the first chamber by a hole. The resonator contains a specific volume of air and has a specific length that is calculated to produce a wave that cancels out a certain frequency of sound.

Fig:- 3 Reactive muffler

It is good practice to design a muffler to work best in the frequency range where the engine has the highest sound energy. In Practice when car is being driven, with the varying engine speed the sound spectrum of an engine speed is continuously changing. It is impossible to design a muffler that achieves complete destructive interference, however some will always occur.

Noise spectrum variation makes muffler design quite difficult and testing is the only sure way to determine whether the muffler performs well at all engine speeds. Exhaust noise is generally limited to the fundamental frequency and the first few harmonics which can be calculated; therefore these frequencies should be used as a starting point for preliminary muffler design.

There is always more than one way to design a muffler for specific applications, however if the designed mufflers is practical and achieves the required noise reduction and meets all functional requirements then the designer has succeeded

III. FUCTIONAL REQUIEMENTS OF REACTIVE MUFFLER

The primary requirements for a practical silencing system are usually the attenuation expressed as a desired insertion loss characteristic or comparable parameter and maximum allowable restriction for an untuned system. Other important requirements are Volume size, back pressure, Temperature effect. Numerous secondary requirements are also present for most designs as listed in Table 1.

Durability
Cost
Ease of manufacture Ease of maintenance
Styling
Tonal quality

TABLE 1 Checklist for Silencer Design

3.1 Insertion loss

The performance of an acoustical muffler is measured in terms of one of the following Parameters:

1 Insertion Loss (IL):- is defined as the difference between the sound power levels, Lw, radiated without any filter (W1) and that with the filter (W2). Mathematically, in dB,

$$IL = Lw1 - Lw2 = 10 \log (W1 / W2)$$

2 Transmission loss (TL):- is independent of the source and requires an anechoic termination at the downstream end. It describes the performance of what has been called “the muffler proper”. It is defined as the difference between the power incident on the muffler proper and that transmitted downstream into an anechoic termination.

3 Noise reduction, NR

Noise reduction (or level difference) is the difference in sound pressure levels Lp at two arbitrary selected points in the exhaust pipe and tail pipe. Unlike the transmission loss, the definition of noise reduction makes use of standing wave pressures and do not require an anechoic termination. Therefore, in dB,

$$NR = Lp2 - Lp1 = 20 \log (p2 / p1)$$

Of the three performance parameters just discussed, insertion loss is clearly the only one that represents the performance of the system truly, because it represents the loss in the radiated power level consequent to insertion of the filter between the source and the receiver (the load). However, it requires prior knowledge or measurement of the internal impedance of the source.

Insertion loss of a lined duct or muffler is limited by the noise generated by the flow of air (or gas) as it comes out of the muffler as a high-velocity jet. This jet noise is augmented by the noise generated at the area discontinuities within the muffler. Analytical estimation of the latter is very difficult. However, Ver has developed an empirical scheme from analysis of voluminous experimental data on the flow-generated noise of duct silencers. This scheme (in the form of three sets of plots) leads to the following empirical formula for sound power level:

Lw(oct) = 10 log{2.16 x 105 V5.4 Sf /(T2.27P4)} (dB)

Where

Lw(oct) is the octave band sound power level (re 10-12 W),

V is the velocity (m/s),

Sf is the face area of the muffler (m2),

T is the temperature of the medium (K), and

P is the open-area fraction.

The octave-band spectrum remains approximately flat over the entire frequency region of practical interest.

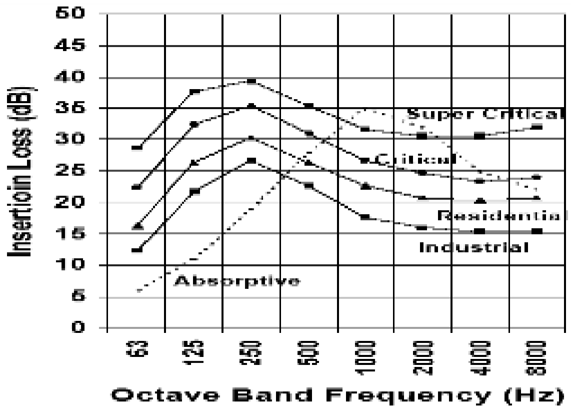


Fig. 4:- Insertion loss (dB) versus frequency (Hz) curve [1]

The maximum possible insertion loss obtainable, if one increases the length of the muffler, is equal to the difference between the upstream power level (incident on the muffler) and the flow generated noise level. Insertion loss beyond this limit calls for not only increased length of the dissipative section but also increased transverse dimensions of the section so that flow passages could be increased and the flow velocities could be decreased.

As general design principle a reactive muffler with many area discontinuities will achieve a greater attenuation than one with fewer area discontinuities.

3.2 Muffler Volume - Size

Based on the experiments and the acoustics theory for muffler design for various Compressor engines, Volume of the muffler (Vm) [3],

$$V_m = V_F \times \frac{\pi}{4} D^2 \times L$$

Where, D = Bore diameter of cylinder of compressor.

L = stroke length of cylinder of compressor.

VF = 10, is muffler volume correction factor.

Muffler Length

According to ASHRAE Technical Committee 2.6, muffler grades and their dimensions, for the super critical grade [4], Length of silencer = 10 to 16 times inner diameter.

Target Frequencies are calculated using formulae:

CFR Cylinder firing Rate

CFR = Engine Speed in RPM/60 …. For a two stroke engine

= Engine Speed in RPM/120 ….For a four-stroke engine

EFR , Engine Firing rate = n X (CFR),

As higher order has very little effect on noise, the diameter of the holes drilled should suppress these frequencies.

3.3 Back Pressure

Back pressure refers to the resistance to a moving fluid by obstructions or tight bends in the confinement vessel along which it is moving, such as piping or air vents, against its direction of flow.

Because it is really resistance, the term back pressure is misleading as the pressure remains and causes flow in the same direction, but the flow is reduced due to resistance. For example, an automotive exhaust muffler with a particularly high number of twists, bends, turns and right angles could be described as having particularly high back pressure.This back pressure is due to loss in stagnation pressure in various tubular elements and across various junctions. When this back pressure is low enough (less than 0.1 bar), it simply represents a corresponding loss in the brake mean effective pressure (BMEP) of the engine

Excessive exhaust constraint can adversely affect performance, resulting in reduced power and increased fuel consumption, exhaust temperatures and emissions. It will also reduce exhaust valve and turbocharger life. It is imperative that exhaust backpressure is kept within specified limits for those engines subject to emissions legislation. When designing an exhaust system, the design target for backpressure should be half the maximum allowable system backpressure.

3.4 Temperature Effects

Exhaust system acoustics are strongly affected by the severe temperature gradients that may be present due to the hot exhaust gases.

For single-cylinder engines, the exhaust gas temperature rapidly decreases along the length of the exhaust system This results in a continuously changing value for the sound velocity used in the various calculations made to determine the frequencies of attenuation maxima and minima.

$$c = 332\sqrt{\frac{\theta}{273}} \quad \text{m/sec}$$

Where Ɵ is the absolute gas temperature (K). In addition, the exhaust gas temperature also varies across the transverse dimension of the muffler, resulting in a complex sound velocity profile. These variations are particularly important for higher-order-mode effects that involve transverse wave propagation in the muffler.

High exhaust system temperatures also cause large thermal expansions to occur in the exhaust silencer and related piping. The thermal stresses generated can cause premature failure of exhaust system components and must be considered in the design process. This is typically accomplished by allowing sufficient movement of the parts to accommodate the thermal expansion without excessive stress on the components.

3.5 Secondary requirement of reactive muffler design.

Proper styling is often important, as are durability and ease of manufacture. Volume, weight, and cost usually place clear limits on the amount of noise reduction possible for a given performance level. Within a given package, these quantities must be balanced to obtain the desired performance. Styling is strongly related to the ease of manufacture and to performance particularly for designs requiring unusual shapes or inadequate volumes. Any reasonable amount of durability is usually attainable through proper design and material selection, although usually at an increase in cost. Some important factors affecting durability are listed in Table 2.

Vibration levels
Resonances of system piping and silencer
Clamps and mounting procedures
Material selection and thickness
Surface coatings
Thermal Expansion

Table 2 Factors affecting Durability

Special requirements may include performance specifications for an intake air filter, exhaust spark arrestor, or exhaust aspirator.

In addition to these performance specifications the designer is usually presented with specific constraints on the geometry and packaging of the silencing system. Typically, silencer placement and piping arrangements are restricted because of operational requirements for the application being considered.

IV. OPTIMISATION TECHNIQUE OF REACTVE MUFFLER DESIGN

Based on the transmission loss and the target frequencies, designer draws few concepts of internal configuration that meets the packaging dimension within the volume mentioned above. Each concept and internal configuration is then formulated to the best possible configuration so as to achieve

best acoustic performance and best (i.e. least) backpressure.

4.1 Perforations: Perforated pipe forms an important acoustic element of muffler, which is tuned in line with the problematic frequencies identified. Size variation on perforated hole diameter can improve muffler performance. The diameter of the hole to be drilled / punched on the pipe is calculated by a thumb rule as given below:

$$d1 = \frac{1.29}{\sqrt{N}}$$

[3]

Where d1: perforated hole diameter

N: Number of holes

4.2 Open area ratio: (Aop)

The open area ratio Aop is given by,

Aop = Area of perforation / Area of the plain sheet.

Lesser the Aop better the transmission loss and better the acoustic performance.

4.3 Expansion Chamber

Expansion Chambers are efficient in attenuating low frequency sound, which make them ideal for automotive applications. Inlet and Outlet diameter are kept same size. The larger the expansion chambers the greater the transmission loss. The length of the chamber should be at least 1.5 times the diameter. [2]

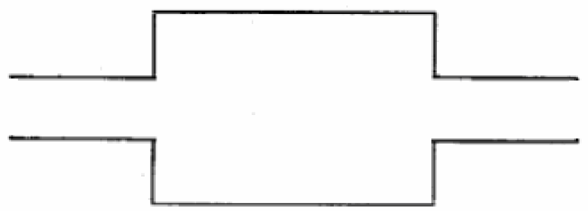
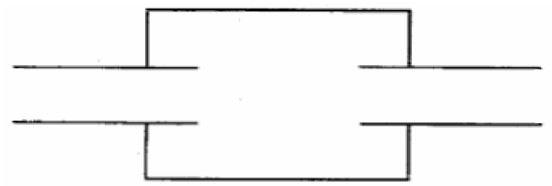


Figure 5:- Simple Expansion Chamber

Figer 6 shows Expansion chamber with extended inlet and outlet. The benefit of such a design is that part of the chamber between the extended pipe and the sidewall act as side branch resonator therefore improving the transmission loss. The grater the protrusion into the muffler the grater the transmission loss.



Figer 6: Expansion chamber with an extended inlet and outlet

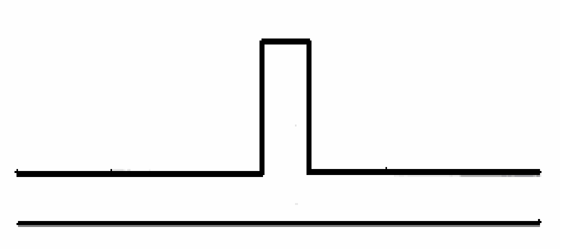


Fig 7:- Side Branch Resonator

Side branch resonator as seen in fig:- 7 is a muffling devise used to direct pure tones of constant frequency. It generally takes the form of a short length if pipe whose length is approximately a quarter if wavelength of sound frequency to be controlled. [2]

If a broader and improved attenuation spectrum is required multiple chambers should be used. Each chamber is used to reduce a specific frequency being an odd multiple of a quarter wavelengths apart.

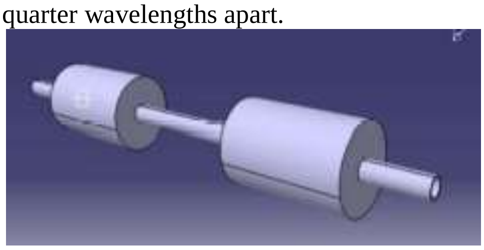


Fig 8 :- Multiple chamber reactive muffler[5]

Fig 9: -Typical muffler with 2 passes

Typical mufflers of the type shown in Fig. 9 generate minimal back pressure, while those of the type multiple chamber.

4.5 MUFFLER SELECTION

- Determine the exhaust flow and acceptable exhaust system backpressure of engine.
- A free-flowing air intake and exhaust system in vehicle.
- Muffler must be built tough to handle high pressure exhaust gasses, absorb impact from road debris, and resist corrosion.
- Number of inlets, single or dual system.
- Diameter of pipe, Inlet and outlet.
- Size of the muffler.
- Material used, stainless steel muffler offers superior corrosion resistance, durability, and life span than the aluminized steel muffler. [4]

Based on this best concepts are designed and carry forward for virtual simulations. Based on above mentioned approach, different concepts will be arrived with optimum combinations of different elements inside volume of the silencer. Finalized concepts will be verified virtually using CAE simulation software's towards the achievement of transmission loss and back pressure.

4.6 CFD ANALYSIS

When steady air flow passes through mufflers, there will have steady pressure drop which is related to flow and geometry of air passages. Pressure drop in an exhaust muffler plays an important role for the design and development of mufflers.

Assumption

- Flow is steady for back pressure and unsteady for T.L.
- Flow considered as Turbulent (K-εModel)
- Air inlet temperature of 120°C
- Sound termination should be anechoic.

Boundary conditions

- Inlet - Velocity inlet of magnitude 25.46 m/sec.
- Outlet - Pressure outlet
- Wall - Perforated pipe wall
- Substrate wall - Porous material wall

Two static pressure monitors at inlet and outlet of perforated pipe are set in fluent. For the CFD analysis of reactive muffler Engine use with below specification.

Engine type	4-stroke DI diesel engine
Number of cylinders	One
Bore x Stroke	87.5 x 110 mm
Compression ratio	16.5.1
Rated power	7 HP
Speed	1500 RPM
Torque	3.5K

Table-3 Engine Specification

Setting the initial and boundary conditions:

The initial and boundary conditions are the premise that the fluid control equation has exact solutions. Its inlet conditions, outlet conditions, wall surface conditions and initial conditions need to be defined when the fluid dynamics of the reactive muffler was analyzed using the Fluent software.

Table 4. Boundary Conditions

Name	Type	Conditons
Inlet	Velocity- inlet	Temperature is 900K, velocity step 20,40,60, 80and 100m/s
Outlet	Pressure- outlet	Atmospheric pressure (101325Pa), Temperature (300 K
Wall	No slip wall	The material is T409L stainless steel, heat transfer coefficient is 100100W/(m2•K), wall thickness is 0.0015m

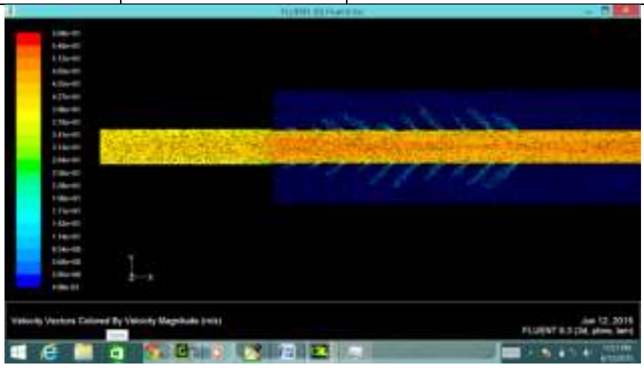


Fig10 :- CFD analysis of straight pipe single chamber using fluent software

This analysis gives visualization of flow in muffler. Also perforated hole performance is observe effectively. This data help for manufacturing of muffler.

V. CONCLUSION

A reactive muffler should be designed to meet all functional requirements as adequate insertion loss, minimal back pressure, temperature effectiveness and space utilization. With these major considerations styling, cost, Durability are also important. Perforated hole size play important role in noise attenuation and insertion loss. Passes increase back pressure but improve noise attenuation. All these consideration are optimized using software tool to check design feasibility virtually. At manufacturing side the design must be proven by its performance on an automobile.

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