General Design Principles for an Automotive Muffler

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ABSTRACT

This paper discusses the general principles of muffler design and explains the main advantages of various styles of mufflers. When designing a muffler for any application there are several functional requirements that should be considered, which include both acoustic and non-acoustical design issues as detailed in this paper.

INTRODUCTION TO AN AUTOMOTIVE MUFFLER

The sole purpose of an automotive muffler is to reduce engine noise emission. If you have ever heard a car running without a muffler you will have an appreciation for the significant difference in noise level a muffler can make. If vehicles did not have a muffler there would be an unbearable amount of engine exhaust noise in our environment. Noise is defined as unwanted sound.

Sound is a pressure wave formed from pulses of alternating high and low pressure air. In an automotive engine, pressure waves are generated when the exhaust valve repeatedly opens and lets high-pressure gas into the exhaust system. These pressure pulses are the sound we hear. As the engine rpm increases so do the pressure fluctuations and therefore the sound emitted is of a higher frequency.

All noise emitted by an automobile does not come from the exhaust system. Other contributors to vehicle noise emission include intake noise, mechanical noise and vibration induced noise from the engine body and transmission.

The automotive muffler has to be able to allow the passage of exhaust gasses whilst restricting the transmission of sound.

MUFFLER DESIGN

There are numerous variations of the two main types of muffler designs commonly used, namely absorptive and reactive. Generally automotive mufflers will have both reactive and absorptive properties.

The reactive or reflective mufflers use the phenomenon of destructive interference to reduce noise. This means that they are designed so that the sound waves produced by an engine partially cancel themselves out in the muffler. For complete destructive interference to occur a reflected pressure wave of equal amplitude and 180 degrees out of phase needs to collide with the transmitted pressure wave. Reflections occur where there is a change in geometry or an area discontinuity.

A reactive muffler, as shown in Figure 1, generally consists of a series of resonating and expansion chambers that are designed to reduce the sound pressure level at certain frequencies. The inlet and outlet tubes are generally offset and have perforations that allow sound pulses to scatter out in numerous directions inside a chamber resulting in destructive interference.

Reactive mufflers are used widely in car exhaust systems where the exhaust gas flow and hence noise emission varies with time. They have the ability to reduce noise at various frequencies due to the numerous chambers and changes in geometry that the exhaust gasses are forced to pass through.

The down side to reactive mufflers is that larger backpressures are created, however for passenger cars where noise emission and passenger comfort are highly valued reactive mufflers are ideal and can be seen on most passenger vehicles on our roads today.

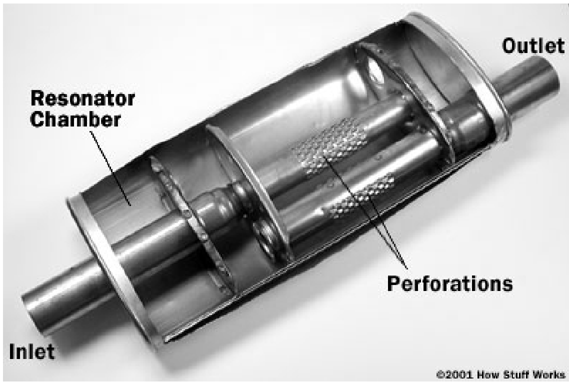

Figure 1: Typical reactive automotive muffler

An absorptive or dissipative muffler, as shown in Figure 2, uses absorption to reduce sound energy. Sound waves are reduced as their energy is converted into heat in the absorptive material. A typical absorptive muffler consists of a straight, circular and perforated pipe that is encased in a larger steel housing. Between the perforated pipe and the casing is a layer of sound absorptive material that absorbs some of the pressure pulses.

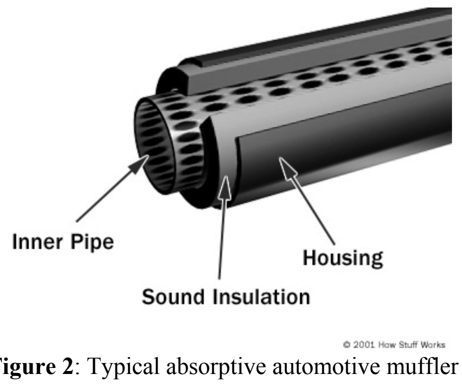

Figure 2: Typical absorptive automotive muffler

Absorptive mufflers create less backpressure then reactive mufflers, however they do not reduce noise as well.

Generally reactive mufflers use resonating chambers that target specific frequencies to control noise whereas an absorptive silencer reduces noise considerably over the entire spectrum and more so at higher frequencies.

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 the sound spectrum of an engine exhaust is continually changing, as it is dependent on the engine speed that is continually varying when the car is being driven. 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. However, as a general rule of thumb, 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.

A practical way of determining the frequency range to be controlled is to measure the unmuffled engine noise. This measured spectrum can then be used to identify the frequencies, at which the higher noise levels occur. The high noise level frequencies should be treated with appropriate noise control to achieve an overall noise reduction.

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

FUNCTIONAL REQUIREMENTS OF A ENGINE EXHAUST MUFFLER

There are numerous functional requirements that should be considered when designing a muffler for a specific application. Such functional requirements may include adequate insertion loss, backpressure, size, durability, desired sound, cost, shape and style. These functional requirements are detailed below focusing on an automotive muffler's functional requirements.

Adequate Insertion Loss

The main function of a muffler is to "muffle" or attenuate sound. An effective muffler will reduce the sound pressure of the noise source to the required level. In the case of an automotive muffler the noise in the exhaust system, generated by the engine, is to be reduced.

A mufflers performance or attenuating capability is generally defined in terms of insertion loss or transmission loss. Insertion loss is defined as the difference between the acoustic power radiated without and with a muffler fitted. The transmission loss is defined as the difference (in decibels) between the sound power incident at the entry to the muffler to that transmitted by the muffler.

The muffler designer must determine the required insertion loss so that a suitable style of muffler can be designed for the specific purpose.

As a general principle when designing an automotive muffler, a reactive muffler with many area discontinuities will achieve a greater attenuation than one with fewer area discontinuities. The addition of sound absorptive material will always increase the attenuation capacity of a muffler, but should be located in an appropriate place.

Backpressure

Backpressure represents the extra static pressure exerted by the muffler on the engine through the restriction in flow of exhaust gasses.

Generally the better a muffler is at attenuating sound the more backpressure is generated. In a reactive muffler where good attenuation is achieved the exhaust gasses are forced to pass through numerous geometry changes and a fair amount of backpressure may be generated, which reduces the power output of the engine. Backpressure should be kept to a minimum to avoid power losses especially for performance vehicles where performance is paramount.

Every time the exhaust gasses are forced to change direction additional backpressure is created. Therefore to limit backpressure geometric changes are to be kept to a minimum, a typical example of this is a "straight through" absorption silencer. Exhaust gasses are allowed to pass virtually unimpeded through the straight perforated pipe.

Size

The available space has a great influence on the size and therefore type of muffler that may be used. A muffler may have its geometry designed for optimum attenuation however if it does not meet the space constraints, it is useless.

Generally the larger a muffler is, the more it weighs and the more it costs to manufacture. For a performance vehicle every gram saved is crucial to its performance/acceleration, especially when dealing with light open wheeled race vehicles. Therefore a small lightweight muffler is desirable.

Effectively supporting a muffler is always a design issue and the larger a muffler is the more difficult it is to support. A muffler's mounting system not only needs to support the mufflers weight but it also needs to provide vibration isolation so that the vibration of the exhaust system is not transferred to the chassis and then to the passenger cabin. This vibration isolation is usually achieved with the use of hard rubber inserts and brackets that isolate or dampen vibration from the muffler to the chassis.

Durability

The life expectancy of a muffler is another important functional requirement especially when dealing with hot exhaust gasses and absorptive silencers that are found in performance vehicles.

Overtime, hot exhaust gasses tend to clog the absorptive material with unburnt carbon particles or burn the absorptive material in the muffler. This causes the insertion loss to deteriorate. There are however, good products such as mineral wool, fibreglass, sintered metal composites and white wool that resist such unwanted effects.

Reactive type mufflers with no absorptive material are very durable and their performance does not diminish with time.

Generally mufflers are made from corrosion resistive materials such as stainless steel or aluminium. Mild steel or aluminised steel is generally used for temperatures up to 500 °C, type 409 stainless steel up to 700 °C and type 321 stainless steel for even higher temperatures. Automotive exhaust gas temperatures are usually around 750 °C.

Desired Sound

Generally a muffler is used to reduce the sound of a combustion engine to a desired level that provides comfort for the driver and passengers of the vehicle as well as minimising sound pollution to the environment.

Muffler designs generally aim to reduce any annoying characteristics of the untreated exhaust noise such as low frequency rumble.

There has however been a growing trend in Australia in recent years for young drivers wanting to “hot up” their vehicles and this includes muffler modification. Muffler modification of a stock vehicle is generally done for two reasons being performance and sound. Vehicles leave the factory floor with mufflers generally designed for noise control not optimal performance. The standard reactive muffler is generally replaced with a straight through absorption silencer for aesthetics and to minimise backpressure and therefore improve vehicle performance.

Having exchanged the stock muffler for an absorptive type performance muffler generally means that exhaust noise is increased, leaving a noticeable deep rumble in the exhaust system. In most cases this sound is what the owner of the vehicle desires so that the public is aware of their presence. However in the main mufflers should be designed so that exhaust noise emission is only barely audible within the passenger cabin and the appropriate government regulations are adhered to.

Breakout noise from the muffler shell may be a problem and should be minimised together with flow-generated noise, especially when designing a muffler for a high insertion loss.

Cost

A major factor in any component is the cost to the consumer. Silencers not only have to be effective in performing their task they need to be affordable otherwise the product will fail in the marketplace. Aftermarket car exhaust mufflers vary in price from $90 to $700.

The cost is dependant on the materials used in the construction of the muffler, design integrity, durability and labour costs.

Shape and Style

Automotive mufflers come in all different shapes, styles and sizes depending on the desired application. Generally automotive mufflers consist of an inlet and outlet tube separated by a larger chamber that is oval or round in geometry. The inside detail of this larger chamber may be one of numerous constructions. The end user of the muffler usually does not care what is inside this chamber so long as the muffler produces the desired sound and is aesthetically pleasing. It is therefore the task of the muffler designer to ensure that the muffler is functional as well as marketable.

POSSIBLE MUFFLER DESIGNS

There are numerous types of automotive mufflers currently in the market place and described below are the key features and benefits of various muffler designs that may be found on a vehicle. The following types of mufflers have been widely tested and the general observations from such tests are described.

Automotive mufflers usually have a circular or elliptical cross section. A circular shaped cross section is best suited in a vehicle as it delays the onset of higher order modes.

Most formulas that are used to predict the transmission loss of a muffler assume plane wave propagation. The properties of the following designs are only valid up to the cut off frequency, where higher order modes occur. Generally for all mufflers maximum transmission loss occurs at odd multiples of a quarter wavelength.

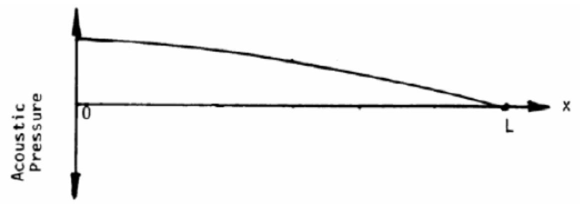

Figure 3: Quarter wavelength

The most basic type of silencing element that may be used for intake and exhaust mufflers is the expansion chamber. It consists of an inlet tube, an expansion chamber and an outlet tube as shown in Figure 4. The inlet and outlet tubes may be coaxial known as a concentric expansion chamber or offset known as an offset expansion chamber.

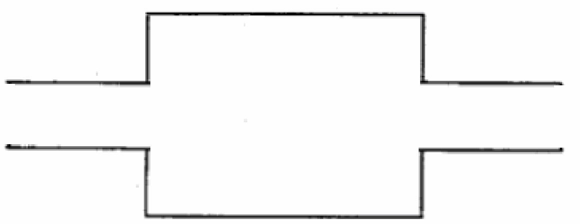

Figure 4: Simple Expansion Chamber

The sudden expansion and contraction in this type of muffler causes sound waves to reflect back and interfere with each other.

Expansion chambers are efficient in attenuating low frequency sound, which makes them ideal for automotive applications. They do not attenuate high frequency sound so well as it ‘beams’ straight through the muffler.

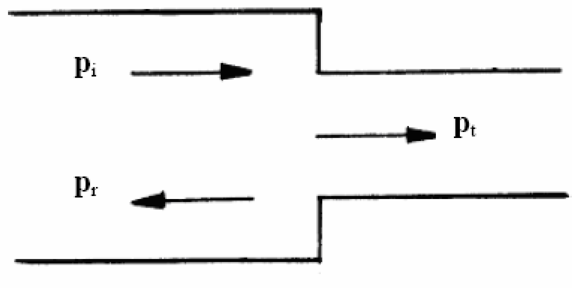

Figure 5: Illustration of the incident, reflected and transmitted sound waves caused by a change in cross sectional area.

Expansion chamber mufflers have been widely studied and results show that the larger the expansion ratio the greater the transmission loss. The length of the chamber should be at least 1.5 times the diameter.

Similar to a standard expansion chamber is the extended inlet and outlet expansion chamber, where the inlet and outlet tubes are extended into the expansion chamber as shown in Figure 6. The benefit of such a design is that part of the chamber between the extended pipe and the sidewall acts as a side branch resonator therefore improving the transmission loss.

The greater the protrusion into the muffler the greater the transmission loss however the inlet and outlet tubes should maintain a separation space of at least 1.5 times the diameter of the chamber to enure the decay of evanescent modes.

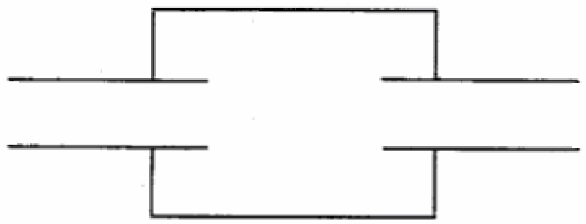

Figure 6: Expansion chamber with an extended inlet and outlet

Noise can be further attenuated by the addition of porous material inside the expansion chamber whilst maintaining the same muffler dimensions. Sound waves loose energy as they travel through a porous medium. The absorptive material (porous material) causes the fluctuating gas particles to convert acoustic energy to heat.

The main benefit of a straight through absorptive silencer, as shown in Figure 7, is that insignificant backpressure is generated therefore improving vehicle performance. The perforated tube is used to guide the exhaust flow and avoids the creation of turbulence as is found in an expansion chamber.

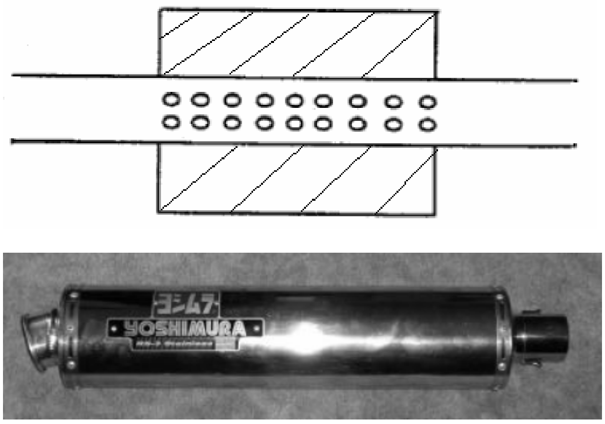

Figure 7: Straight through absorption muffler

The material used to guide the exhaust flow, yet allow sound waves to escape, is usually perforated steel with an open area of approximately 20%.

An absorptive silencer produces a more consistent transmission loss (TL) curve as shown in Figure 8. The expansion chamber TL curve is typically domed in shaped and as can be seen the absorptive material not only irons out these humps but also increases transmission loss dramatically especially for the higher frequencies.

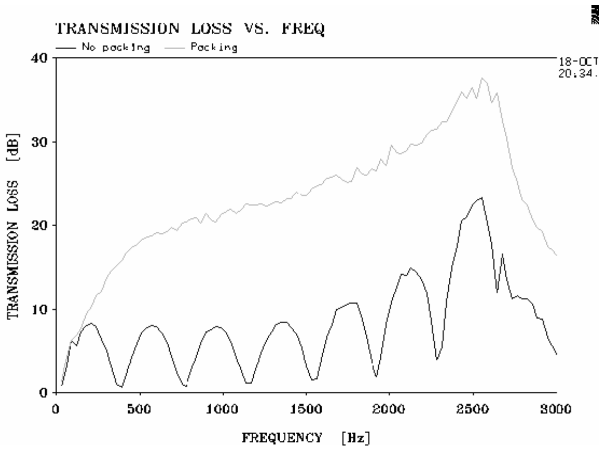

Figure 8: Comparison of a muffler with and without absorptive material

A side branch resonator as seen in Figure 9 is a muffling device used to control pure tones of a constant frequency. It generally takes the form of a short length of pipe whose length is approximately a quarter of the wavelength of the sound frequency to be controlled. A Helmholtz resonator is similar to a side branch resonator the only difference being that there is a backing volume joined to the connecting orifice.

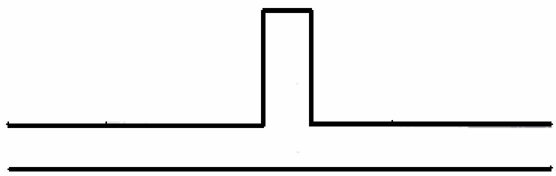

Figure 9: Side branch resonator

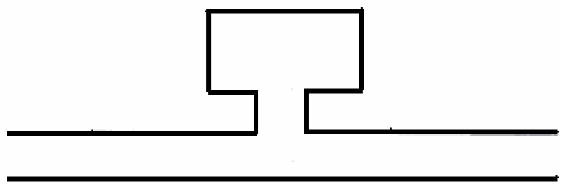

Figure 10: Helmholtz resonator

If it is found that the unmuffled exhaust noise spectrum has noticeable peaks a resonating chamber (concentric resonator) muffler or a side branch resonator may be used, as shown in Figure 11, to target these specific resonant frequencies. The resonating chamber style of muffler is extremely efficient in providing noise control for a specific frequency band; however the attenuation band is very narrow. This characteristic is not very useful in automotive exhaust system where attenuation is needed over all frequencies. A side branch resonator may be however used in addition to a muffler to treat a particular problem frequency.

If a broader and improved attenuation spectrum is required multiple resonators should be used. Each chamber is designed to reduce a specific frequency being an odd multiple of a quarter wavelength apart. Attenuation is increased as the number of chambers increase although the addition of a third chamber only provides a small increase in attenuation. If a tube connects the chambers, the longer the tube the greater the attenuation achieved. This type of muffler is useful when space is limited and low frequency performance is required.

The volume and shape of the resonating chamber govern its performance capabilities. Generally as the volume of the resonating chamber increases the resonant frequency reduces.

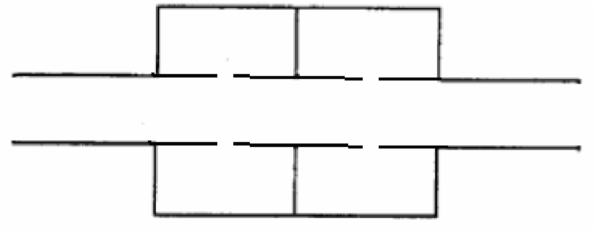

Figure 11: Resonating chamber muffler

MEASURED PERFORMANCE OF AN ABSORPTION STYLE MUFFLER

The insertion loss of an absorptive muffler fitted to a Formula SAE vehicle has been measured to assess this style of muffler and its attenuation characteristics. This performance vehicle uses a straight through absorptive muffler as it provides the required attenuation of 18 dBA as well as being lightweight and produces minimal backpressure for increased engine performance.

The specifications of this muffler (Yoshimura RS-3) are: inner diameter of 57 mm; outer shell diameter of 112 mm; length of 457 mm; 1.6 mm perforated tube running from the inlet to the exit pipe with 1160 perforations that are 3.2 mm in diameter. A layer of absorptive material is sandwiched between the perforated tube and the outer casing.

Exhaust noise measurements were made at 0.5 m and 45 degrees from the end of the exhaust outlet with the microphone of a B & K Precision Sound Level Analyser at the exhaust outlet level.

The unmuffled and muffled exhaust noise spectrums of the 2004 University of Sydney Formula SAE vehicle can be seen in Figure 13 below. The insertion loss of this muffler was measured to be (128 – 110) = 18 dBA.

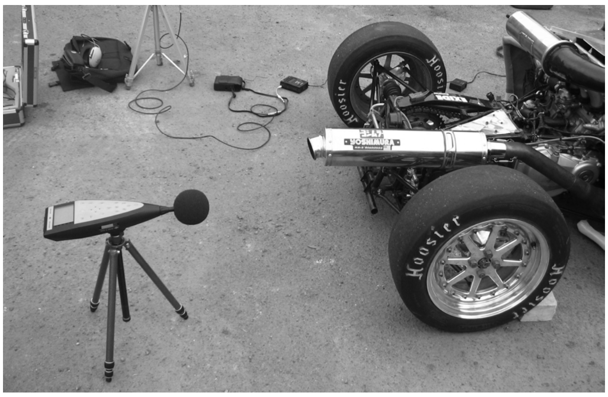

Figure 12: Measurement setup

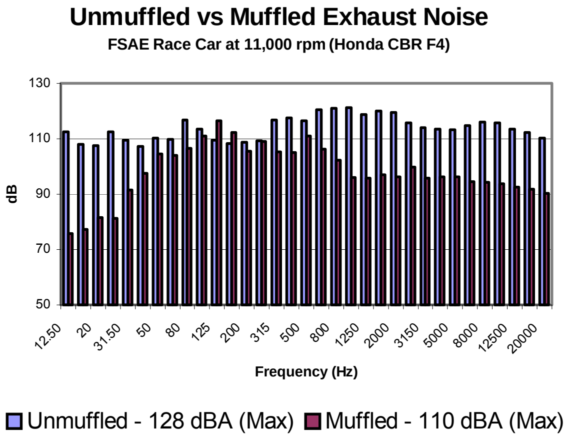

Figure 13: Muffled vs. unmuffled engine exhaust noise

It was noticed when measuring the unmuffled engine noise that at idle speeds the unmuffled noise spectrum showed less energy in the higher frequencies than at 11,000 rpm. The high frequency noise at high engine speed can be attributed to the increased velocity of the exhaust gasses. At 5,500 rpm the 500 Hz band is the dominant frequency, which equates to the third harmonic, however at 11,000 rpm there is no clear dominant frequency but substantial amounts of energy can be seen at the fundamental frequency (367 Hz), third (1,100 Hz) and fifth (1,835 Hz) harmonics as expected.

The measurements show that this absorptive muffler is a good broadband attenuator and controls noise extremely well at the low frequencies and the high frequencies. The absorptive material provides all the high frequency attenuation as expected of such a muffler and the resonating effect of the central chamber is controlling the mid to low frequencies.

It is interesting to note that the noise level at 125 Hz increased when the muffler was added to the exhaust pipe. This is not an uncommon occurrence and is caused by the resonance of the new system due to the extra mass and stiffness associated with the muffler. The increased noise level at 125 Hz is not a concern as when the noise spectrum is A-weighted, to adjust for human hearing, the 125 Hz frequency is adjusted by –16 dB and therefore the contribution at this frequency is negligible to the overall noise level.

The 18 dBA noise reduction could be improved with the use of a reactive style of muffler, however this absorptive muffler was chosen as it is ideal for such an application as it provides the required attenuation, is lightweight and produces little backpressure for increased engine performance.

CONCLUSION

A vehicle muffler should be designed to meet all functional requirements as mentioned above, namely adequate insertion loss, minimal backpressure, space constraints, be durable, produce the desired sound, be cost effective and be aesthetically pleasing. There will be many possible muffler design solutions for a particular situation and many possible ways to predict a mufflers insertion loss but the design is proven by its performance on an automobile.

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