Chapter 2

Literature Survey

In the earlier chapter importance of muffler and silencer was discussed. Various types of mufflers and silencers, their effects were studied along with their performance parameters. The focus of this chapter is to review the most relevant research that has been undertaken in the area of passive mufflers/silencers and optimization methods.

Exhaust noise has long been recognised as the primary noise source of an internal combustion engine. Mufflers have been used to control this noise for many years. Although the study of mufflers, particularly those used with reciprocating combustion engines, has been of interest for many years, the increased public awareness of noise issues and stringent regulations have provided an impetus to improve the performance of these devices.

An acoustic filter theory approach for silencer design was first developed by Stewart and Lindsay [5]. In this theory the propagation of sound is considered one dimensional. Other features which are not considered in this theory are mean flow, effect of tail pipe reflections, mean temperature variation, interaction between mean gas flow and sound in the region of disturbed flow at the discontinuities. Miles [31] has shown that reflection of sound energy towards the source is generally achieved by introducing area discontinuities and flow reversals in the sound path. Thus the transmission of sound energy can be reduced by inserting appropriate discontinuities in the muffler system.

The expansion chamber was analytically modeled by Davis et al. [32] in the early 1950s for plane wave propagation assuming linear acoustics with no flow and a theoretical equation for TL of a simple expansion chamber was then developed. The NACA report by Davis et al. [32] was one of the first comprehensive attempts to model mufflers. They
used the transmission line theory by assuming both continuity of pressure and continuity of volume velocity at discontinuities and also many factors such as geometry, porous material properties, and flow effects to predict the acoustic performance of a muffler. Sreenath and Munjal [33] adopted electro-acoustic analogies to compute insertion loss of a muffler.

A large amount of work has been published since then on the basis of the plane wave theory for the prediction of muffler performance [34, 35]. Alfredson [36] has shown that the acoustic performance of a circular duct of continuously varying cross section area can be predicted with good accuracy by dividing the duct into a number of parallel subsections with small discontinuities at the end of each subsection. Acoustic performance of an expansion chamber in a duct as a sound attenuator is represented by the repeating dome shaped transmission loss curves when the plane wave theory is applied. But when the axial length of chamber is considerably reduced or diameter increased, this property changes remarkably and the chamber begins to act as a resonator muffler [37]. Munjal et al. [16, 38] used the mass velocity instead of volume velocity with a different definition for the acoustic impedance of filter elements and analyzed number of mufflers of arbitrary shapes and complex combinations.

In order to predict the acoustic performance parameters of mufflers, in terms of transmission loss, the four pole parameters of ducts and mufflers need to be evaluated. The transfer matrix method based on plane wave theory has been widely used in one dimensional analysis of exhaust muffler systems and it provides a very convenient and useful way to model and analyze acoustic systems, because it allows formulating the transfer matrices for different elements independently and combining them by simple successive multiplication [38]. Transmission loss can be predicted very easily from the known physical parameters of the muffler and is only a property of these four pole parameters [12,29] and independent of the source and the termination impedances. The major disadvantage of transfer matrix method (four pole parameters method) is that it suits only one dimensional system and the higher order mode effects in wave propagation are neglected. In conclusion the theory fails to predict the transmission loss at higher frequencies where modes other than the plane wave are cut-on. In spite of these drawbacks acoustic filter theory was extensively used by investigators to predict the transmission loss of several types of engine exhaust silencers.
In general, sound waves propagating along a pipe can be attenuated using either a resonative or a reactive muffler. Resonative and reactive mufflers, which are commonly used in automotive applications, reflect 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, and requires the use of acoustic transmission line theory. The expansion chamber muffler is a reactive type muffler where a portion of sound energy is always reflected when a sudden change in cross section is encountered. It has been shown analytically that a reflective muffler works by reducing the resistive component of the load impedance seen by the source, as compared to the atmospheric impedance that the source would see in the absence of the muffler. Thus the reactive muffler acts on the principle of impedance mismatch [12, 39].

Kim and Soedel [40] developed a general method to formulate four pole parameters of muffler using modal expression. The propagation of multidimensional waves in expansion chambers is dependent on the length of the chamber as well as the expansion ratio and frequency. Multidimensional waves are excited at all frequencies at the area discontinuities of the chamber, however, for frequencies well below the cut-off frequencies, the multidimensional waves decay in a short distance and have little effect on the transmission loss. At higher frequencies approaching that of the first radial mode, multidimensional effects begin to dominate causing the repeating domes behavior of the expansion chambers to break down. As the expansion chamber length becomes short the repeating dome behavior breaks down altogether as the length of the chamber is no longer sufficient for the higher order modes to decay and these higher order modes can significantly affect the performance of expansion chamber mufflers [41, 42]. The presence of these modes sharply reduces the attenuation above the cut-on frequency for the mode that is excited. The lengths of the chamber of an industrial muffler are not large enough; as a result, three dimensional evanescent modes are easily excited and alter the performance of the muffler considerably [41].

Selamet and Radavich [43] investigated the effect of length on the acoustic attenuation performance of concentric expansion chambers. They showed that mufflers having \( l/d = 3.5253 \), the contours are planar throughout the chamber at very low frequencies; however with increasing frequencies, some non-planar contours begin to appear at the area discontinuities due to the fact that the transition excites higher order radial modes. When
the frequency is below that for which these modes can propagate freely, the non-planar
modes decay exponentially with distance and only planar behavior is observed away from
the area transitions. As the frequency becomes closer to the propagating or the cut-on
frequency for the first radial mode, the modes do not decay as quickly and the multi-di-
ensional effects spread throughout the length of the chamber. Contours for the short $l/d$
ratio chamber indicate the importance of the multidimensional propagation even at low
frequencies. Higher order modes are excited at the expansion and due to the short length
of the chamber they do not decay sufficiently. So for the muffler elements with shorter
length to diameter ratios, or for higher ranges of $kl$, multidimensional analysis methods
should be used because the 1-D method may not predict all of the resonances or even any
of the resonances, in the frequency range of interest [44]. Sedamoto and Murakami [45]
investigated resonant properties of short expansion chambers using the traditional analyt-
ical approach treating a duct system as a distributed parameter system and depending on
chamber length which becomes half of axial wavelength of the incident $(m, n)$ mode; and
the $(m, n+1)$ mode becomes cut-on in the chamber.

Over the past decades researchers have discovered that the propagation of three dimen-
sional acoustic modes, i.e. higher order modes can significantly affect the performance of
classical expansion chambers [41, 42, 46–48].

It has been shown that reflection of sound energy (towards the source) is generally
achieved by introducing area discontinuities and flow reversal in the sound path. How-
ever these discontinuities also introduce substantial pressure drop in the fluid flow. To
avoid pressure drop in the fluid flow, perforated tubes have been used to guide the flow.
Sound energy also gets dissipated while moving through the perforations and adds to the
attenuation. Sullivan and Crocker [49] presented the first analysis of perforated element
silencers with a closed form series expansion solution for straight-through silencer ele-
ments. Sullivan [50,51] then developed a segmentation analysis, in which the effect of the
perforations is lumped into a few discrete planes with solid pipes assumed to be present
between the planes. This approach is extremely flexible in that it can be used to model
any geometrical situation, including multi-pipe elements. This modeling is extremely
useful and perforated tubes are used intelligently in combination with area discontinuities
and flow reversals to fabricate reflective, perforated element mufflers with better sound
attenuation characteristics with lesser back pressure [52, 53]. Variable area elements with
perforated elements have also been used in this regard [54].

Mufflers based on the principle of conversion of acoustic energy into heat by means of highly porous fibrous linings are called dissipative silencers. Attenuation of acoustic waves in the absorbing material is mainly due to viscous and thermal dissipation. When sound propagates in small spaces, such as the interconnected pores of a porous absorber, energy is lost. This is primarily due to viscous boundary layer effects. Air is a viscous fluid, and consequently sound energy is dissipated via friction with the pore walls. There is also a loss in momentum due to changes in flow as the sound moves through the irregular pores. The boundary layer in air at audible frequencies is sub millimetre in size, and consequently viscous losses occur in a small air layer adjacent to the pore walls. Apart from viscous effects, losses occur due to thermal conduction from the air to the absorber material. These losses are more significant at low frequencies.

The reduction of sound energy using absorptive materials is achieved by transferring the acoustical pressure (wave motion) into material motion. This mechanical motion is converted into heat (energy loss) by material damping and friction. The more effective the sound wave penetrates the material the more effective the attenuation. Each baffle assembly consists of compartments and the basic theory considers each compartment as locally reacting where the acoustic sound wave pumps in and out through the material as well as through the perforated facing sheet or pack material retainer. The perforation pattern adds damping and frictional losses to the aero-acoustic wave oscillating through the holes; the smaller the holes and more the perforations, the more will be attenuation. The packing consists of absorptive material that is principally fibrous material or open cell foam that allows the wave energy to penetrate, induce material motion and be attenuated. The acoustic modeling of simple silencer geometries, such as circular or rectangular cross sections, has been established and classified depending on the assumptions of locally or bulk reacting lining. Morse [55] used a locally-reacting model to investigate the sound transmission in pipes with absorbing material on the inner walls. Scott [56] studied the transmission of sound in infinite rectangular and circular ducts. Ko [57] investigated the characteristics of sound attenuation for rectangular, annular and circular ducts. Acoustic characteristics of the porous layer facing perforations were investigated by Ingard and Bolt [58], who considered the perforations as addition of mass. Due to the complex structure of absorbing material, these acoustic properties are often determined
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experimentally [59].

The exhaust systems of internal combustion engines generate noise with a wide frequency range, including particularly strong low frequency components and high frequency components. In such applications, effectiveness of dissipative silencers can be enhanced by reactive acoustic elements. The combination of dissipative and reactive components defines the hybrid silencer, which is an effective noise attenuator over a wide range of frequencies. These mufflers may also include extended double tuned expansion chambers and extended concentric tube resonators as relatively recent development. The TL spectrum of simple expansion muffler consists of periodic troughs. In order to nullify or raise these troughs one needs to use the resonance peaks due to extended lengths such that they exactly nullify the troughs. In order to achieve this one needs to calculate the exact geometric lengths of these extensions with the help of end corrections. These end corrections need to be calculated by three dimensional FEM analysis and by experiments. The presence of extended inlet/outlet ducts in a hybrid silencer is known to provide an acoustic attenuation performance in which a combination of broadband domes and resonant peaks is found below the onset of the first excited higher-order mode [18]. Selamet et al. showed that by suitable selection of the lengths of extended ducts, it is possible to match the resonances with the pass-band frequencies, thus improving the acoustic behaviour over a wide frequency range for single-chamber mufflers [18] as well as multiple-chamber configurations [19]. This enhancement of the transmission loss is primarily associated with the low and mid frequency range, where planar propagation dominates the acoustic field.

Hybrid silencers commonly have multiple chambers connected to each other by ducts. The interactions among these chambers may substantially affect the overall performance of hybrid silencers. Thus, the design of hybrid silencers requires understanding of acoustic characteristics of individual dissipative and reactive elements, as well as the interactions among them. These dissipative silencers may have many kinds of sound absorbing or isolating materials, such as glass wool, polymeric fibrous materials, and various types of foams, alone or with viscous and elastic materials. Z. L. Ji [60] investigated the combined behaviour of reactive and dissipative silencer. He concluded that the resonator contributes a primary low frequency (around 180 Hz) resonance and several narrow peaks at higher frequencies, while the absorptive chamber provides an effective acoustic attenuation at
higher frequencies. The filling sound absorbing material in the expansion chambers improves acoustic attenuation and removes the troughs in transmission loss of the reactive silencer.

The acoustic performance is usually quantified by the frequency-dependent sound transmission loss. A variety of methods have been used to predict this quantity for mufflers, ranging from analytical and computational methods to experimental techniques. However, practical muffler configurations generally have large cross sectional dimensions as well as complex geometries and analytical methods are cumbersome in the sense that the associated algebra is very complicated. Hence it is impossible to solve such problems by analytical methods.

The numerical methods are completely general and with the ever-increasing computational speed and storage capacity of computers, the use of the finite element method (FEM) in design is growing rapidly and allows the analysis of all types of mufflers.

In order to perform the TL calculations by FEM, the desired region is divided into a grid of nodes and elements. The fundamental theory behind FEM shows that each element interacts only with the elements directly adjacent to it. With wise node numbering, the result is a banded coefficient matrix for the resulting system of equations, which can be solved faster than a full coefficient matrix. Since the entire acoustic domain is considered for calculation, there also exists the ability to assign different element types, and material properties (such as porosity and density) to different sections of the mesh. This is useful when trying to properly model absorptive materials.

The acoustic behavior of an expansion chamber lined (locally reacting) with absorbing material has been investigated by Craggs [61] using the finite element method. He has shown that (1) the absorbing material increases the magnitude and changes the shape of transmission loss, and (2) increasing the thickness of absorbing material reduces the number of domes and shifts the peak frequencies of transmission loss. Kirby and Cummings [62] extended this work by investigating two types of perforations, circular and louvered plates, with and without porous backing. Arenas and Crocker [63] studied the conical, exponential, parabolic, adenoidal and cosine shaped connectors to connect two pipes of different cross sectional areas and proved that all the connectors possess a similar behavior for very low frequencies which is equal to TL of a single discontinuity, but at higher frequencies for all the connectors, the TL tends to zero. Bilawchuk and Fyfe [64]
compared various numerical methods for calculating the transmission loss in silencers. Selamet et al. [19] applied mode matching technique to predict the acoustic behavior of concentric circular dual-chamber mufflers and various effects have been studied including the presence of a baffle inside the muffler, the baffle hole radius, the axial location of the baffle and the extension of inlet and outlet ducts. Dowling and Peat [26] described an efficient algorithm for acoustic analysis of any general silencer system by recording the order in which all of the elements are analyzed and the subsystems are reduced. Mehdizadeh and Paraschivoiu [65] described a faster three point method for the evaluation of the transmission loss and concluded that FEM can perform computations in the entire domain and is therefore more powerful. More specifically, FEM is able to address problems in heterogeneous domains. Broatch et al. [66] analyzed simple geometries with well known acoustic behavior and concluded that good results may be obtained from any numerical method if the mesh spacing is sufficiently small but small meshes may imply an excessive computation time. Wu et al. [67] have shown that the higher order mode effects manifest differences between the computed TL values and those calculated by the plane wave theory for the acoustically short chambers for higher frequencies.

The results achieved by numerical tool i.e. by FEM may not be correct due to many reasons such as modeling errors, meshing errors, assumptions while solving the partial differential equations (solution errors), specifications of approximate boundary conditions, insufficient constraints, selection of meshing elements, types of meshing etc. Irrespective of these drawbacks numerical methods have been used extensively by investigators to predict the transmission loss of several types of engine exhaust mufflers/silencers.

The muffler dimension is often limited inside a building or a machine room; more so in an automobile because of severe space constraint. Research on muffler design has been well addressed; however, the severe constraints problem has hardly been mentioned. Jae-Eung Oh and Kyung-Joon [68] proposed optimal design scheme to improve the muffler’s capacity of noise reduction of the exhaust system by combining the Taguchi method and the fractional factorial design. In the first stage of design they selected the length and radius of each component of muffler as control factors and in second stage the fractional factorial design to take interactions into considerations. From the signal to noise (S/N) ratio optimum control factors were devised to get maximum transmission loss.

Mohanty and Pattnaik [69] proposed optimal design methodology for a family of
perforated mufflers based on one dimensional analysis. Min-Chie Chiu et al. [70] optimised shape of single-chamber mufflers with side inlet/outlet by using boundary element method, mathematical gradient method and genetic algorithm in dealing with the elimination of pure tone noise of 500 Hz under space constraints. To increase the acoustic performance, a three-chamber side muffler hybridized with an inner perforated tube which may dramatically depress the sound energies is proposed by Min-Chie Chiu [71] and optimised by using simulated annealing (SA) method.

From the literature review it is observed that optimization of muffler under space constraint is addressed scantily and this study has great scope for design of mufflers with increasing demand on performance.

2.1 Summary

This chapter summarizes the literature survey done to derive the research perspective, in the domain of reactive and absorptive silencers. Initially, reactive mufflers, with their working principles, theory and analysis were extensively studied. Further, absorptive silencers and hybrid silencers were studied. The research carried out to address 3-D effects and improving performance of mufflers and silencers was studied in detail. All multidimensional analyses may be subject to more geometric approximations in practical applications due to more coordinates or dimensions being modeled. But if the given geometry of the muffler is close to an idealized shape for modeling then it gives accurate results. The analytical, numerical and experimental methods in analysis and design, their strengths and limitations were studied. Optimization methods like grid search, Taguchi and ANOVA methods were studied. The limitation of current state of art for designing optimized muffler and silencer led to future course of this work.

Before beginning the analysis of muffler it is useful to study basic aspect of acoustics, acoustic variables, basic relations, wave propagation, one dimensional wave equation, their limitations and evaluation of analytical methods for the prediction of muffler/silencer performance which has been presented in the next chapter.