Any research for the development of specific component of system requires the conceptual knowledge of the whole system in which component has to be fitted. This chapter discusses the conceptual background of some fundamental to evaluate noise reduction technique. 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. The present literature review includes the study which had been made up till now on the noise reduction of acoustic reactive mufflers.

The review of muffler noise reduction is based on the following points:

1. Study on mathematical model of muffler.
2. Study on muffler parameters by simulation tool.
3. Experimental measurement techniques for noise reduction on muffler.
4. Study on sound quality of mufflers.

2.1. STUDY ON MATHEMATICAL MODEL OF MUFLER

Munjal M. L. et al., [42] investigated the Integration of side inlet and/or side outlet expansion chambers into the rest of the muffler system for prediction of overall transmission loss (TL) or insertion loss requires knowledge of the four-pole parameters of these elements for propagation of plane waves in a moving medium. Lamancusa J. S. et al., [43] derived the mathematical model for the double expansion chamber muffler is a commonly used for the silencing element in duct noise applications. The transmission loss for the case of equal size
chambers is known and easily calculated. A closed form expression for the transmission loss for the case of chambers of unequal length and area is presented. Demir A. et al., [44] suggested that the propagation of sound in an infinite rigid cylindrical duct with an inserted expansion chamber whose walls are treated with an acoustically absorbent material is investigated rigorously through the Wiener–Hopf technique. Norman K. R. et al., [45] has shown that an alternative exhaust manifold system the Perforated Manifold Muffler and Catalyst (PMMC) is proposed to improve sound suppression while reducing engine pumping losses and exhaust emissions. This results in reduced engine pumping work and thus improved engine brake horsepower. Additionally conservation of exhaust gas thermal energy and the reduced thermal inertia of the exhaust system provide earlier catalyst light-off and therefore reduced pollutant emissions. Sathyanarayana Y. et al., [46] presents a new hybrid approach for prediction of noise radiation from engine exhaust systems. It couples the time domain analysis of the engine and the frequency domain analysis of the muffler, and has the advantages of both. Various results of this approach are compared with those of the method of characteristics and the classical acoustic theory, and various peaks and troughs in insertion loss curves are analytically validated. El-Sharkawy A. I. et al., [47] derived the acoustic equations are derived for the general case of sound wave propagation in circular ducts. The exact and approximate methods for solution are reviewed, analyzed and compared for the purpose of ICE muffler design. Different types of mufflers are also presented; their attenuation properties are estimated according to different theoretical approaches. Selamet A. et al., [48] Proposed acoustic behavior of a circular dual-chamber muffler and investigated in detail by: (1) a two dimensional (2-D) axis symmetric analytical approach based on the mode-matching technique for the
concentric configurations; (2) the finite element method and then compared experimentally. Yeh L.J., et al., [49] explained the optimal design of a single chamber muffler with side inlet/outlet is comprehensively presented. Both the graphic analysis and the computer-aided numerical assessments are also fully described in this study. This study demonstrates a quick and economical approach to optimize the design for a single-chamber muffler with side inlet/outlet under space constraints without redundant testing. Chiu M.C. et al., [50] presented in his paper, the four-pole system matrix used in evaluating acoustic performance is derived by using the decoupled numerical method. Moreover, a simulated annealing (SA) algorithm, consequently, the approach used for the optimal design of noise elimination proposed in this study is certainly easy and efficient. An acoustic filter theory approach for silencer design was first developed by Uno Ingard [51]. 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 [52] 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. [53] 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. [53] 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 [54] 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 [55,56]. Alfredson [57] 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 [58]. 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 [59]. 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 [26] 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 [26]. Kim and Soedel [60] 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 [61]. 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 [61]. Selamet and Radavich [62] 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 multidimensional 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 [63]. Sedamoto and Murakami [64] investigated resonant properties of short expansion chambers using the traditional analytical 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. Simple expansion
chambers have very limited practical application due to the presence of periodic troughs in the transmission loss spectrum which drastically lower the overall transmission loss of the muffler. Tuned extended inlet and outlet can be designed to nullify three-fourths of these troughs, making use of the plane wave theory. These cancellations would not occur unless one altered the geometric lengths for the extended tube in order to incorporate the effect of evanescent higher-order modes (multidimensional effect) through end corrections or lumped inertance approximation at the area discontinuities or junctions. Chaitanya and Munjal [65] studied the effect of wall thickness of the inlet/outlet duct on end correction which is a consequence of the evanescent higher order modes generated at the area discontinuities. This has significant effect on the tuning of an extended inlet/outlet expansion chamber. 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. However 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 [66] presented the first analysis of perforated element silencers with a closed form series expansion solution for straight-through silencer elements. Sullivan [67, 68] 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 [69, 70]. Variable area elements with perforated elements have also been used in this regard [71]. The commercial automotive mufflers are generally of a complicated shape with multiply connected parts and complex acoustic elements. The analysis of such complex mufflers has always been a great challenge. Vijayasree and Munjal [72] developed an Integrated Transfer Matrix (ITM) method to analyze transmission loss of complex, multiply connected mufflers. ITM relates the state variables across the entire cross-section of the muffler shell, as one moves along the axis of the muffler, and can be partitioned appropriately in order to relate the state variables of different tubes constituting the cross-section, which can then be used to evaluate the transmission loss, insertion loss. To improve the acoustic performance of an existing muffler or each acoustic element or a combined component used in the muffler should be focused. Yasuda et al. [73] proposed muffler which can attenuate the noise of low frequency and middle frequency at the same time by introducing interconnecting holes and Helmholtz resonator on the tailpipe. Banerjee and Jacobi [74] proposed single-inlet-double-outlet (SIDO) and double-inlet-single-outlet (DISO) mufflers to reduce back pressure without much effect on transmission loss (minor loss in TL) by observing broadband attenuation characteristics. Over the past decades researchers have discovered that the propagation of three dimensional acoustic modes, i.e. higher order modes can significantly affect the performance of classical expansion chambers [61]. The location of the inlet and outlet ports also can significantly influence the attenuation characteristics of a muffler system. Min-Chie Chiu et al. [75] optimized 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 acoustical 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 [76] and optimised by using simulated annealing (SA) method. Lima et al. [77] showed a Genetic Algorithm (GA) methodology used in the optimization of purely reactive silencers associating parametric optimization with the shape optimization in order to define the appropriate size of the inlet and/or outlet ducts to modify the transmission loss curve in specific frequency ranges. Chiu [78] addressed muffler's optimal shape design to overcome a broadband noise hybridized with multiple tones within a constrained space and proposed hybrid mufflers composed of a reactive unit, a dissipative unit, and Helmholtz resonator units to promote the best acoustical performance in mufflers. 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.

2.2. STUDY ON MUFFLER PARAMETERS BY SIMULATION TOOL

Selamet A., et al., [79] explained the acoustic attenuation of a single-pass, perforated concentric silencer filled with continuous strand fibers is investigated first theoretically and experimentally. Multi-dimensional BEM predictions of a hybrid silencer demonstrate that a reactive component such as a Helmholtz resonator can improve transmission loss at low frequencies and higher duct porosity may be effective at higher frequencies. Broatch A. et al., [80] explained a comparative study of the performance of different schemes used to solve one-dimensional gas flow equations when applied to the computation of the frequency response of exhaust mufflers is presented. The results provide guidelines for a
proper choice of the numerical scheme, taking into account the mesh spacing. Ramakrishnan R. et al., [81] presented Passive silencers with acoustic fill such as glass fiber, rock wool or foam are commonly used in conventional heating, ventilation and air conditioning systems. Insertion loss of the silencers is estimated from attenuation rates calculated from a finite element method. Good comparison between the current model and the test data was also observed. Barbieri R. et al., [82] describes a methodology which combines finite element analysis and Zoutendijk’s feasible directions method for mufflers shape design. The main goal is to obtain the dimensions of the acoustic muffler with the transmission loss (TL), being maximized in the frequency range of interest. Wu C.J. et al., [83] presented the acoustical performance prediction on single inlet/double-outlet (SIDO) and double-inlet/single-outlet (DISO) expansion chamber mufflers with rectangular section. Expressions for the transmission loss (TL) of this kind of mufflers are formulated by using the collocation approach. Numerical results of TL are compared with the plane wave theory to show up the higher-order mode effects. Furthermore, the finite element method (FEM) is also employed again to verify its accuracy in view of these configurations of muffler. Andersen K.S. et al., [84] presented Analyzing Muffler Performance Using the Transfer Matrix Method. The transfer matrix is the basis for calculating either the insertion loss or transmission loss of a muffler. The 3D simulations in Comsol of different muffler configurations are verified by measurements in a flow acoustic test rig using the two source method. The past work in this field thus concentrate mainly on experimental & on mathematical modeling for a specific area to find out the transmission loss. A FEA based analysis on the internal cross section area for different shapes is not reported in literature so far. Hence the work aims FEA of Exhaust gas through the different path area also incorporate the effect of
material on muffler for the analysis of Transmission Loss. Munjal et al. [30] 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. Mimani and Munjal [85]
presented with the 3-D semi-analytical method for the elliptical chamber mufflers
having an end-inlet and a side-outlet and showed that an appropriate position of
the ports can lead to the suppression of the propagation of higher order modes,
resulting in a broadband attenuation. 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 [32]. 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 behavior
over a wide frequency range for single-chamber mufflers [32] as well as multiple
chamber configurations [33]. 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 [86] 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 [87] 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 [88] extended this work by investigating two types of perforations, circular and louvered plates, with and without porous backing. Allam [89] 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 [90] compared various numerical methods for calculating the transmission loss in silencers. Selamet et al. [33] 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. Wu et al. [91] 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. Jae- Eung Oh and Kyung-Joon [92] 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 [93] proposed optimal design methodology for a family of perforated mufflers based on one dimensional analysis. Exhaust Sound quality is play an important role for the customer [94,95].

2.3. EXPERIMENTAL MEASUREMENT TECHNIQUES FOR NOISE REDUCTION ON MUFFLER

Ghosh B.B. et al., [96] predict the pressure drop is very important tool for the design of muffler. It has solved by one-dimensional wave equation by the method of separation variables using boundary conditions. Afterward to validate the theoretical results such as noise level, Engine performances, Brake thermal efficiency, Brake specific fuel consumptions with the existing muffler and the modified designed and fabricated muffler. Yasuda T. et al., [97] explained the tail pipe noise from a commercial automotive muffler was studied experimentally and numerically under the condition of wide open throttle acceleration. M.B. Jadhav, A. P. Bhattu, [98] proposed experimental setup is developed to predict the acoustic performance of reactive silencer by using two load method and it is validated by determination of transmission loss (TL) of known reactive muffler model by using finite element method (FEM). For the model experimental measured transmission loss was compared with that obtained from the finite element method (FEM). From the result it can be concluded that developed setup

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is reliable to determine TL by experimental method from low to mid frequency range.

2.4. VEHICLE SOUND QUALITY IMPROVEMENT BY USING MUFFLER

Hatti, [99] proposed the application of these advanced CAE methods used in the development of our new small Gas Turbo Direct Injection Eco-Boost engines and DCT transmissions. These new powertrains have achieved impressive levels of quietness and smoothness. The contents of the presentation will detail analytical methods for powertrain structural NVH design, as well as Air Induction & Exhaust system acoustics analysis for achieving best Sound Quality performance. Patidar, [100] proposed noise source contribution results validated the exhaust and intake systems should be improved first to fulfill a favorable sound quality. Combining the objective, subjective and source contribution results, this study successfully synthesized a promising and feasible vehicle level sound target. It was then cascaded to get the synthesized intake and exhaust noise targets for next CAE design modification. P. Hetherington, [101] proposed a time domain engine/exhaust simulation program is used to calculate the engine order content of the tailpipe radiated noise from an odd fire V-10 exhaust system. Both steady state and transient conditions are simulated and sound files generated for exhaust sound quality evaluation. To increase the realism of played back sounds, the predicted engine orders are mixed with synthesized or recorded background noise for both steady state and transient conditions. Carsten Sartorius, [102] proposed Aim of the exhaust system development is to reach future target values of the pass-by noise and sound engineering for the vehicle. Therefore it's necessary to use an engine simulation tool with the capability of a
very detailed muffler modeling. This paper describes design investigations of an exhaust system for a V-6 gasoline engine for a new vehicle by using WAVE 1-D and KADOS.

2.5 JUSTIFICATION OF THE NECESSITY OF THE PRESENT WORK

From the above literature review it is observed that a number of substantial researches have been made on mathematical modeling, experimental work, simulation tool as well as sound quality for specific purpose, but still it is in primary stage. So a combined study on quality of sound analysis in generalized manner not yet to be reported with special consideration by validation through different simulation approach.

In the present work to optimize the performance of noise attenuation of muffler has been done with space constraints with cylindrical shape. Transmission loss performance of muffler can be improved by making small modifications in muffler’s design like extended inlet and outlet, perforation on baffle and intruding tubes, use of quarter wave tube and helmholtz resonator, use of hybrid muffler by with the modification on pure reactive muffler having constant volume. The present work has thus led to development of a simple technique of designing a complex effective optimized hybrid muffler by using with FEA tool and validation by experimental setup.

Before beginning the analysis of muffler the basic aspect of acoustics, basic acoustic terms, basic relations, one dimensional wave propagation equation and their limitations is necessary to evaluate of analytical methods for the prediction of muffler (silencer) transmission loss performance which has been done in this study.