Recent Advances in Muffler Acoustics

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Exhaust noise in engines has always been a major source of automotive noise. Challenges for muffler design have been constraints on size, back pressure, and, of course, the cost. Designing for sufficient insertion loss at the engine firing frequency and the first few harmonics has been the biggest challenge. Most advances in the design of efficient mufflers have resulted from linear plane wave theory, making use of the transfer matrix method. This review paper deals with evaluating approximate source characteristics required for prediction of the unmuffled intake and exhaust noise, making use of the electroacoustical analogies. In the last few years, significant advances have been made in the analysis of variable area perforated ducts, transverse plane wave analysis of short elliptical as well as circular chambers, double-tuned expansion chambers and concentric tube resonators, catalytic converters, diesel particulate filters, air cleaners, etc. The development of long strand fibrous materials that can be used in hot exhaust systems without binders has led to the use of combination mufflers in exhaust systems. Breakthroughs have been achieved in the prediction and control of breakout noise from the elliptical and circular muffler shell as well as the end plates of typical mufflers. Diesel particulate filters and inlet air cleaners have also been modeled acoustically. Some of these recent advances are the subject of this review paper.

1. INTRODUCTION

Mufflers are essentially low-pass acoustical filters. Making use of electroacoustical analogies,[1] lumped inductance and capacitance of electrical wave filter are represented in mufflers by connecting pipes (or ducts) and chambers (or plenums), respectively. Helmholtz resonators of musical acoustics have also found their counterpart here in the form of a hole-cavity resonator. Although the science of acoustics of ducts and mufflers is over 150 years old,[2] the first comprehensive experimental investigation on analysis and design of mufflers for internal combustion engines was reported by Davis et al. in 1954.[3] The classical 1-D or plane wave theory with progressive waves moving in either direction led to the development of the transfer matrix method (TMM), which is ideally suited for acoustical modelling of cascaded elements constituting typical automotive mufflers.[4]

The TMM makes use of the standing wave variables to move from one element to the next in the cascade. Computationally, successive multiplication of transfer matrices is much faster as well as more convenient than formulation and simultaneous solution of a large number of linear algebraic equations. In fact, a heuristic study of the transfer matrix multiplication process led to the development of a user-friendly algebraic algorithm,[5] which in turn helped in a rational synthesis of 1-D acoustical filters[6] as well as vibration isolators.[7]

Morfey's work on the sound generation and propagation in ducts with mean flow[8] indicated that the convective effect of mean flow[9] is to augment the flow-acoustical power of the forward wave and reduce that of the rearward (or reflected) wave. This led to the definition of convective (or flow acoustical) state variables (p_c, v_c) that are linearly related in the classical (stationary medium) state variables (p, v). Replacement of (p, v) with (p_c, v_c) yields identically similar expressions for insertion loss (IL) of a muffler with incompressible mean flow.[10] The transformation relations between (p, v) and (p_c, v_c) enable conversion of the transfer matrices in classical state variables with a moving medium to their counterparts in convective state variables and vice versa.

A Helmholtz resonator introduces a sharp peak at its resonance frequency.[10] However, designing an automotive muffler requires wide-band domes. Therefore, a designer would use pipes with extended perforations opening into an annular cavity. The resulting concentric tube resonator was first modelled by Sullivan and Crocker,[11] making use of a 1-D control volume approach. The resulting coupled equations were solved by writing the acoustical field in the annular cylindrical cavity as a summation of natural modes satisfying the rigid-wall boundary conditions at the two ends. Sullivan followed it up with a segmentation approach which was applicable to a configuration with even three interacting ducts.[12] Munjal, Narayana Rao, and Sahasrabudhe developed a generalized decoupling approach for such perforated-element configurations.[13,14] This approach was soon followed by Peat's eigenvalue analysis,[15] which was particularly tailored for digital computation, where we can make use of the standard subroutines or library functions. A parametric study by Munjal, Krishnan, and Reddy yielded a relative flow-acoustical performance of concentric tube resonators, plug mufflers, and chambers with three interacting ducts.[16] Empirical expressions for the stagnation pressure drop for all three types of perforated-element muffler configurations were derived in terms of the open-area ratio of the perforate.[16]

Over the next decade, a large amount of research was reported on acoustical analysis of complex perforated elements,[17–24] particularly the open-end flow-reversal elements[24] and acoustical characterization of the exhaust and intake system of the reciprocating internal combustion engines.

Automobile engine is a variable speed engine, and therefore, a muffler must act as a low-pass filter with adequate wide-