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A REVIEW OF FLOW ACOUSTIC EFFECTS ON A COMMERCIAL AUTOMOTIVE EXHAUST SYSTEM

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RESEARCH ARTICLE

ABSTRACT: Acoustic simulation methods are being increasingly used for practical exhaust system design of automotive. In many practical applications, the sound source emits, partly, a low frequency sound spectrum comprised of superposed discrete tones and partly, a higher frequency broadband spectrum. The turbulent vortices that develop in the boundary layer between the duct wall and the flowing medium are said to generate a self-excited noise, that noise is broadband character. The self-excitation is enhanced when the flow is disturbed by irregularities in the duct wall. Unsteady compressible fluid flow through a duct is often encountered in many engineering applications and has been investigated by many researchers. When a pressure wave generated inside a duct is discharged from an open end of the duct, an impulsive wave that is usually characterized by high sound pressure level of short duration forms at the vicinity of the exit of the duct. Acoustic simulations solve the equations for motion, mass, momentum, and energy and can be divided into two methods, linear and non-linear. Through that literature review, we can analyse the methods and the latest development done on exhaust systems with regard to acoustic performance. The basic theory behind both approaches is explained as well as a source characterization technique that can be used to link the two methods. Some acoustic software tool has been applied to a variety of exhaust systems.

KEY WORDS: computational fluid dynamics (CFD), aeroacoustics, exhaust system, Helmholtz resonator, flow effect, transmission loss, muffler modeling

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PREGLED AKUSTIČNIH EFEKATA PROTOKA NA KOMERCIJALNI AUTOMOBILSKI SISTEM

REZIME: Metode akustične simulacije se sve više koriste u praktičnom dizajnu izduvnih sistema automobila. U mnogim praktičnim primenama, izvor zvuka emituje, delimično, niskofrekventni zvučni spektar koji se sastoji od superponiranih diskretnih tonova i delimično širokopojasnog spektra veće frekvencije. Turbulentni vrtlozi koji se razvijaju u graničnom sloju između zida kanala i srednjeg toka stvaraju samo-pobuđeni šum, koji je širokopojasnog karaktera. Samo-pobuđivanje je pojačano kada je protok poremećen nepravilnostima u zidu kanala. Nestabilni protok stišljivog fluida kroz kanal se često susreće u mnogim inženjerskim primenama i istraživan je od strane mnogih istraživača. Kada se talas pritiska koji se stvara unutar kanala ispušta iz otvorenog kraja kanala, impulzivni talas koji se obično karakteriše visokim nivoom zvučnog pritiska je kratkog trajanja u blizini izlaznog kanala. Akustičke simulacije rešavaju jednačine za kretanje, masu, moment i energiju i mogu se podeliti na dve metode, linearne i nelinearne. Kroz taj pregled literature, možemo analizirati metode i najnoviji razvoj koji se radi na izduvnim sistemima s obzirom na akustične performanse. Osnovna teorija koja stoji iza oba pristupa objašnjena je kao i tehnika karakterizacije izvora koja se može koristiti za povezivanje ova dva metoda. Neki akustični softverski alati su primenjeni na različite izduvne sisteme.

KLJUČNE REČI: računska dinamika fluida (CFD), aeroakustika, izduvni sistem, Helmholtz rezonator, efekat protoka, gubitak prenošenja, modeliranje prigušivača

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1. INTRODUCTION

Noise is therefore studied, regulated and monitored by many countries, authorities, and establishments due to the negative effects. Noise from the transportation sector, and more specifically road vehicles with internal combustion engines is something people interact within a day-to-day basis making it an important area for noise control. Manufacturers of all kinds of road vehicles strive to mitigate as much noise as possible to produce silent vehicles both due to legislation and competition.

Knowledge of the acoustic source characteristics of internal combustion engines (IC-engines) is of great importance when designing the exhaust duct system and its components to withstand the resulting dynamic loads and to reduce the exhaust noise emission. The goal of the present review is to show numerically and experimentally investigate the variety speed IC-engine acoustic source characteristics, not only in the plane wave range but also in the high frequency range define the wave equation one must first look at one – dimensional the linear conservation equation of continuity which relates density and particle velocity up in the medium. The decomposed definition of density have been inserted and higher-order terms are neglected [1].

2. MATHEMATICAL MODELS

The sound usually generated because of the coupling between the turbulent average flow field and the acoustic field is said to be self-excited. The solution to the wave equation; the general solution for free, plane and one-dimensional wave propagation:

$$P(x, t)= f(t-x/c)+g(t+x/c) \tag{1}$$

Where f and g are arbitrary functions. f(t-x/c) implies wave propagation in the positive direction along the x-axis, with the speed c and P(x, t) represent sound pressure.

We can write the linear conservation equation of continuity:

$$\frac{\partial \rho}{\partial t} + \rho o \frac{\partial u_p}{\partial x} = 0 \tag{2}$$

Where:

ρ: Acoustic density disturbance kg/m^3

ρo: Density in undisturbed medium kg/m^3

The linear in viscid conservation equations of momentum are also needed. Assuming that viscous effects can be neglected, the equation system relates velocity of the sound wave with acoustic pressure. Here, higher-order terms are also neglected.

Linear in viscid of motion:

$$\rho o \frac{\partial u_p}{\partial t} + \frac{\partial P}{\partial x} = 0 \tag{3}$$

Equation (1) and (2) include five unknown variables to solve but only four equations, similarly, as in fluid dynamics, the equation of state must be used to complete the equation system. Thermodynamic equation of state:

$$(p_o + p) = (\rho o + \rho)RT/M \tag{4}$$

Where:

Po: Pressure in undisturbed medium Pa

Pac: Acoustic pressure Pa

R: Ideal gas constant (R = 8.315) J/(mol. K)

The gas low for adiabatic changes of state:

$$\frac{(Po + P)}{Po} = \left(\frac{\rho o + \rho}{\rho o}\right)^{\gamma} \tag{5}$$

he acoustic wave equation can then be defined by subtracting the time derivative of continuity (2) from the spatial derivative of momentum (3) and eliminating ρ by inserting the equation of state (4). The governing acoustic wave equation is defined as:

Source-free linearized acoustic wave equation:

$$\frac{\partial^2 p}{\partial x^2} - \frac{1}{C^2}\frac{\partial^2 p}{\partial t^2} = 0 \tag{6}$$

The speed of sound expressed as:

$$C = \sqrt{\gamma Po/\rho o} \tag{7}$$

γ :Turbulence intermittency defining the propagation speed of an acoustic wave in the medium. The temperature dependence of the speed of sound:

$$C = Co\sqrt{T/273} \tag{8}$$

Where Co is the speed of sound at 0 °C.

There is important part in mufflers called Helmholtz Resonance chamber formed by a part of the inlet pipe and chamber is to reduce the specific frequency noise. It acting as an acoustic filter is designed to attenuate low frequency noise from engine [3]. The effects of mean flow on the acoustic properties of Helmholtz resonator and frequency domain-based Computer Aided Engineering (CAE) can describe the acoustic properties without mean flow. But to be able to design effective resonators with consideration for flow effects, a computational technique able to capture the fluid physics and acoustic behavior in the time-domain accurately is necessary. A simplified way of describing the interaction between fluid flow and acoustic wave propagation is applying the linearized Navier-Stokes equations (LNSE) [4].

$$fr = \frac{c}{2\pi}\sqrt{\frac{A_n}{V_c(L_n + \delta_n)}} \tag{9}$$

Where:

fr: Cut-off frequency

C: The speed of sound

A_n: The neck cross-sectional area

V_c: The volume of the resonator house

L_n: The length of the neck

δ_n: The end correction.

2.1 Transmission loss

There are several acoustic quantities to define the noise mitigating performance of a silencer in a duct system. The most common quantities are noise reduction (NR), insertion loss (IL) and transmission loss (TL). The NR is defined as the difference in sound pressure level (SPL) before and after the muffler. The most accepted approach today is the approach developed by authors [2] who proposed a two-source method for measuring the four-pole parameters of an acoustic element or combination of elements. The method can also be used in the presence of a mean flow.

2.2 Decomposition method

This method used for calculation transmission loss. TL with decomposition method can be expressed as:

$$TL = 10Log_{10}\frac{W_i}{W_t} \tag{10}$$

Where Wi, Wt denote incident and transmitted sound power level of the acoustic wave present in the exhaust-duct system. The equation can be written in other form to express the transmission isolation of an expansion chamber with a circular cross section and eccentrically placed inlet and outlet point:

$$D_{TL} = 10.\log(1 + (\frac{S_1}{2S_2} - \frac{S_2}{2S_1})^2 sin^2(kL)) \tag{11}$$

Where:

S_1: Cross section area of incoming of channel

S_2: Cross section area of outgoing of channel

K: Wave number

L: The length of chamber

2.2.1 Two-Source Method

The two-source method is based on the transfer matrix approach that represents the acoustic behavior of the muffler.

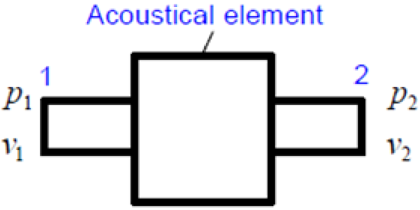

Figure 1. The four-Pole method

The transfer matrix is

$$\begin{bmatrix} P_1 \\ V_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} P_2 \\ V_2 \end{bmatrix}$$

Where P_1 and P_2 are the sound pressure amplitudes at the inlet and outlet, respectively; V_1 and V_2 are the particle velocity amplitudes at the inlet and outlet, respectively; and *A*, *B*, *C* and *D* are the four-pole parameters of the system [5].

2.2.2 Two-Load Method

The transmission loss measurement setup schematically as shows in figure 2. A speaker is placed at the end of the impedance tube. Two microphones are mounted upstream and the other two microphones are mounted downstream. Two different termination loads are applied, and four transfer functions are measured for each load [6].

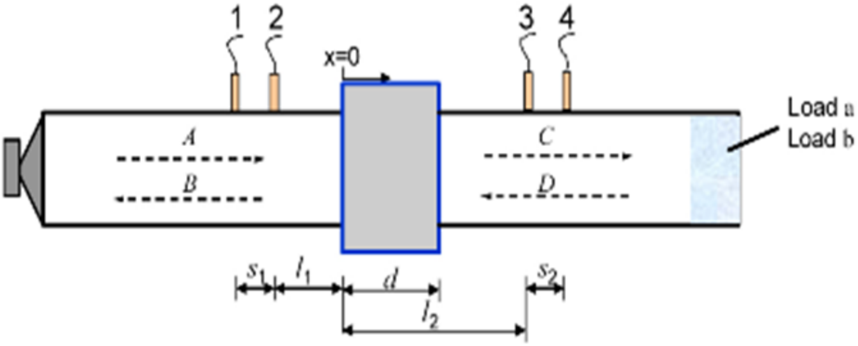

Figure 2. Two-load transmission loss test setup [6]

Tao and Seybert, studied and compared the results from two source method and two-load method calculation of transmission loss in mufflers which do not require an anechoic termination, as shows in figure 3.

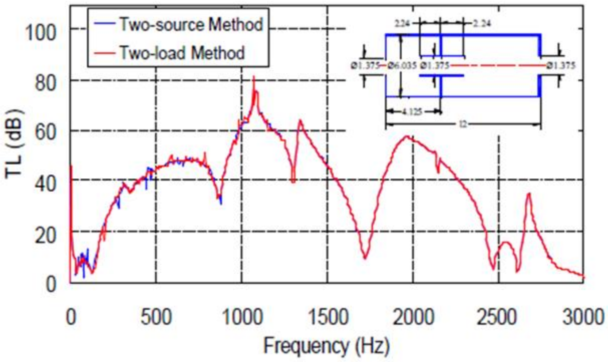

Figure 3. Validation between Two-source method and two-load method (Muffler dimensions in inches) [6]

3. SOFTWARE ANALYSIS

3.1 Software description and calculation

This chapter aims to present the numerical methods used in the further simulations to describe the mathematical models presented in literature. Only numerical methods related to CFD and how the methods are implemented in Ansys - Fluent are of interest. This means that numerical methods related to the acoustic. Authors [7] study acoustic using simulation software based on the linear and nonlinear approach and the solutions to the basic fundamental equations for mass, momentum, and energy. The results was implied that the linear acoustic simulation can then be used to predict radiated sound and take advantage of the faster calculation times. Increasing use of after treatment devices in exhaust systems requires specific models of such components. This method is also able to utilize optimization techniques which are particularly well suited to the fast calculation speed of the linear acoustics. Authors [8] Investigate numerically and experimentally at the medium speed of internal combustion engine acoustic source characteristics and at high frequency range. One-dimensional process simulation code was used for this study. The design of exhaust system was done according to engine standard parameter.

Authors [9] discuss the transverse plane wave analysis of short elliptical end chambers, acoustical source characterization of the exhaust systems of reciprocating internal combustion engines, analysis of multiply-connected element mufflers, breakout noise of non-circular muffler shells, and analysis of porous inside the muffler.

Recently, Authors [10] have presented a two-port method for flow and pressure drop calculation as well as acoustical analysis of complex perforated-element automotive mufflers. The study proposed a new segmentation approach based on two-port analysis techniques in order to model perforated pipes using general two-port codes, which are widely available.

3.2 Flow distribution

When flow is introduced through the muffler, its transmission properties are affected in three ways. The first is through the convective effects, which affect the propagation inside straight pipes. This effect was accounted for in the formulation of the transfer matrices for different pipe elements. The second is the introduction of extra losses at the area expansion, which takes place at the end of the inlet pipe. The third and most important effect of flow is introduced by the change of the perforate impedance. The flow can be either grazing to the perforate, through the perforate, or both. The bigger effect comes from the flow through the perforate, which increases the resistance considerably.

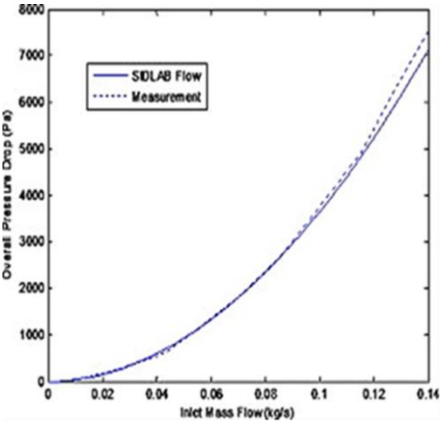

Figure 4. Pressure drop inside the prototype muffler [10]

Authors [11] considered the problem of wave propagation in short elliptical chambers having ports located along the major axis of the elliptical section. The wave propagation was considered along with the transverse direction (along with the major axis), wherein. Matrizant method was used to obtain transfer matrices relating the upstream and downstream variables. It was pointed out that such short chamber muffler characterized by dominant transverse plane wave propagation is acoustically analogous to an extended inlet and outlet chamber. In fact, a short chamber shows a striking resemblance with a side inlet and side outlet chamber (long in the axial direction). A prerequisite for this investigation is to have realistic values of the pressure-time history. These were computed using the commercial software AVL-BOOST for different acoustical loads [12]. This finite-volume CFD model is used in conjunction with the two-load method to evaluate the source characteristics at a point in the exhaust pipe just downstream of the exhaust manifold.

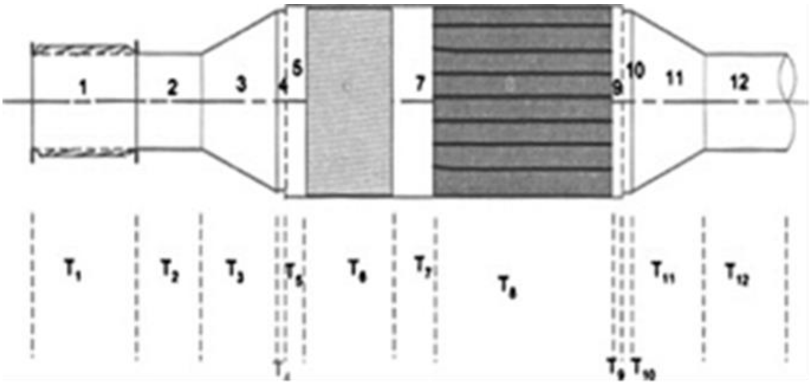

Figure 5. Sketch of the muffler internal scheme [11]

Authors [13] study muffler performance experimentally and a test rig was designed in order to measure the Transmission Loss of a set of muffler configurations in the stationary medium. The experimental set up is based in a combination of the decomposition method. It shows the geometry and comparison between the experimental and Transfer Matrix Method (TMM) modeling numerical results of TL for a high porosity perforated concentric tube inside an elliptic expansion chamber. A reasonable similarity in the transmission loss curves can be verified.

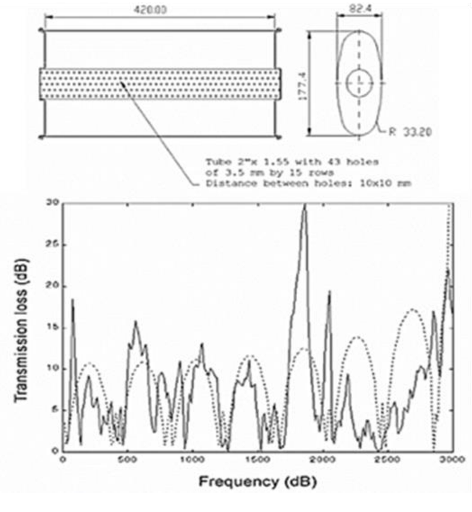

Figure 6. Transmission loss of a concentric perforate tube; TMM results and experimental result [13]

Authors [14] present a new hybrid approach or prediction of noise radiation from engine exhaust systems by making use of the time domain modeling of the cylinder and cavity pipe junction, and the linear frequency domain analysis of the muffler.

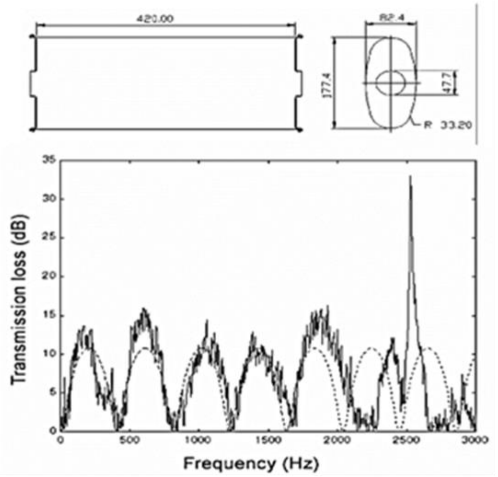

Figure 7. Transmission loss for a simple expansion chamber using an extended tube length of 0.1 mm [13]

Authors [15] had analyzed an elliptical expansion-chamber muffler as well as an end chamber muffler using a 3-D analytical method based on the modal superposition technique and the point-source method. In this figure below, the 1-D model based on the transverse plane-wave method is used to predict the transmission loss characteristics of short axial-length mufflers, taking the same dimensions as considered.

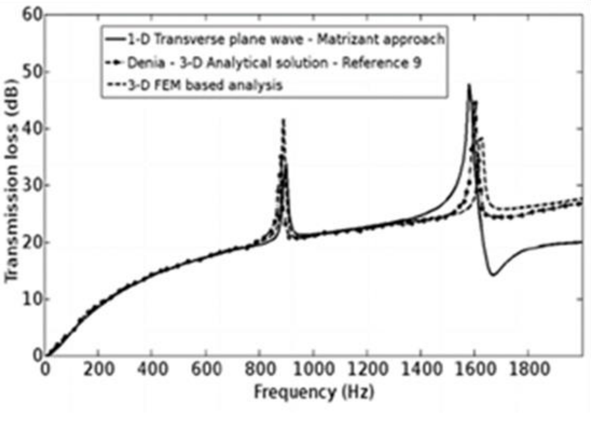

Figure 8. Acoustic performance of end-centered inlet and end-offset outlet configuration, as shown in Fig. 8a with L = 0.05 m, D 1 = 0.23 m, D 2 =0.033 m [15]

Authors [16] presented in their technical paper, the performance of circular duct with non-locally lining by numerically and experimentally. The liner concept is based on perforated screens backed by air cavities. Dimensions of the cavity are chosen to be bigger than the wavelength so acoustic waves within the liner can propagate parallel to the duct surface. The aim of this research was to identify the best multi-cavity muffler configuration for reduction of exhaust noise from the engine. The result shows that the cavity configuration achieving the maximum overall acoustic Transmission Loss. The study also illustrates how the acoustic performances are dependent on the nature of the incident field.

Authors [17] analyzed the limitation of the net insertion loss of the muffler, by using three-pass double reversal muffler in automotive exhaust systems. This muffler is characterized by a fairly wideband transmission loss [TL] curve as well as relatively low back pressure.

Authors [18] prove experimentally, the ratio of the reduction in the back pressure at 11000 engine rpm is around 40% with open valve, as compared closed valve condition. The increase in sound transmission loss, with closed valve, is around 15~20 dB higher when compared to open valve condition. M. Dixit et al. studied the effects of back pressure on muffler effectiveness and the simulation is carried out using GT-POWER® tool. The discretization of muffler and resonator shell and pipes for element generation had played an important role in the proper prediction of back pressure and thereby reducing valuable design cycle time and cost. Authors [19] presented in their technical paper optimization of intake exhaust system of a single-cylinder water-cooled swirl chamber diesel engine, by using computational fluid dynamics [CFD] and steady flow test method. The configurations and performances of intake and exhaust port, air filter and muffler were optimized for reducing flow resistance, increasing charge amount and lowering residual exhaust gas, leading to the improvement of engine performances and emissions, e result of this research show great achievement in engine exhaust gas properties. Authors [20] presented in their research paper the acoustic characteristics of duct muffling systems. The program was based on the plane wave theory and uses the Visual Basic 6.0 to build and modify the duct muffling systems quickly with proper the geometrical and physical parameters, to examine the effects of design changes on the acoustic attenuation characteristics and finally to get an acceptable solution.

Authors [21] was contributed to determine acoustic performance of muffler and can be reviewed for design and development of muffler. In his research paper two-load method was conducted for measuring muffler transmission loss also algorithm for computing the transmission loss was involved. It is demonstrated that the effect of adding conical adapters is significant at low frequencies especially if the adapter is short in length. It was found that measurements are improved by selecting a downstream microphone as a reference instead of an upstream microphone with good agreement for both method.

The author [22] use an acoustical topology optimization for a partition volume minimization problem achieving high value transmission loss through muffler.

Authors [23] used Computational Fluid Dynamics (CFD) methods for simulation of acoustic pulse in muffler and develop a full compressible Navier-Stokes solution algorithm for acoustic propagation problems. A new hybrid low Mach number pressure based compressible solver was developed to simulate propagation of pulses of random shape, demonstrated by application through a simple expansion muffler.

Authors [24] compared model meshing approach result with numerical analysis in various cases of length–diameter ratio to predict transmission loss of a muffler. Authors [25] studied the automotive muffler experimentally and numerically. 3D CFD was used to evaluate both mean flow and acoustic performance of an expansion chamber muffler, with various modifications including baffles an extended inlet or out let pipes.

Authors [26] studied acoustic plane wave properties of a complex geometry, and some parameter were experimentally calculated such as reflection coefficient using the TMM on the upstream and downstream side of the test object. In this research Presented and tested a method for measuring the two-port data in the form of a scattering-matrix, describing the relationship between the traveling wave amplitudes of the pressure on either side of the test object.

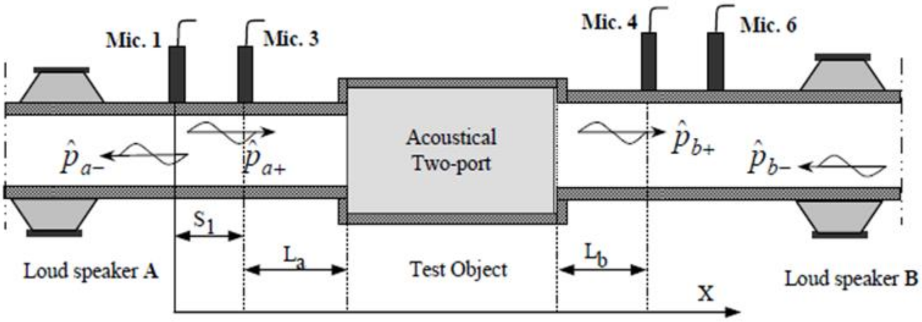

Figure 9. Acoustical Two-Part method for a muffler [26]

Linear and passive two-port in the frequency domain, be written:

$$X=TY \tag{12}$$

Where, X/Y are the state vectors at the input/output and T is a [2×2]-matrix, which is independent of Y. To determine T, from measurements four unknown must be determined.

The transfer-matrix form uses the acoustic pressure P and the volume velocity V.

X = [P_a, V_a] and Y = [P_b, V_b] here [a] and [b] represent two different ducts cross section. The transfer-matrix could be written in the following form:

$$\begin{bmatrix} P_a \\ V_a \end{bmatrix} = \begin{bmatrix} T_{aa} & T_{ab} \\ T_{ba} & T_{bb} \end{bmatrix} \begin{bmatrix} P_b \\ V_b \end{bmatrix} \tag{13}$$

$$Pa = P+exp(-ikaLa)+P-exp(ikaLa) \tag{14}$$

$$V_a = \frac{A_a}{\rho c}\{(P_+exp(-ik^aL_a)-P_-exp(ik^aL_a)\}$$

and

$$P_b = P_+exp(-ik^bL_b)+P_-exp(ik^bL_b)$$
$$V_b = \frac{A_b}{\rho c}\{(P_+exp(-ik^bL_b)-P_-exp(ik^bL_b)\} \tag{15}$$

The result shows, the acoustic two port, of a single diaphragm orifice and then validated with the theoretical result has been calculated using 3D FEM software FEMLAB from other literatures.

The author [27] present different approaches for measurement and evaluation of the source characteristics of an engine exhaust system have been briefly reviewed, with particular emphasis on their relative implications and limitations. These approaches combine the advantages of the frequency-domain analysis of mufflers with those of the time-domain analysis of the exhaust manifold source. Because in some method does not require prior knowledge of the source characteristics, like piston motion, exhaust valve/port opening and high blow-down pressure in the cylinder.

4. CONCLUSIONS

The main contribution of the present review, as well as the development of an expression for the non-dimensional frequency for obtaining the resonance peak in the TL graph for the short chambers with end ports, is another noteworthy contribution of this present review. This enables a muffler designer to have a quick estimate of the positions of the peak and trough in the TL spectra for short chamber mufflers and to get a qualitative understanding of the basic nature of such short chamber mufflers.

REFERENCES

[1] Linus Zackrisson. Flow Acoustic Effects on a Commercial Automotive Air Intake Silencer A Numerical Study using Computational Fluid Dynamics. *Journal of Applied Mechanics*. Chalmers University of Technology, 2017.

[2] M. L. Munjal, and A. G. Doige. Theory of a Two Source-location Method for Direct Experimental Evaluation of the Four-pole Parameters of an Aeroacoustic Element. *Journal of Sound and Vibration*, Vol.141, No. 2, 1990, pp 323-333.

[3] Takashi Yasuda, Chaoqun Wu, Noritoshi Nakagawa and Kazuteru Nagamura. Studies on an automobile muffler with the acoustic characteristic of low-pass filter and Helmholtz resonator. *Applied Acoustics,* Volume 74, Issue 1, 2013.

[4] Hans Bodén, Ulf Carlsson, Ragnar Glav, Hans-Peter Wallin, and Mats Åbom. *Sound and vibration*. The Marcus Wallenberg Laboratory, KTH, 2003.

[5] Z. Tao and A. F. Seybert. A Review of Current Techniques for Measuring Muffler Transmission Loss. *Society of Automotive Engineers*, Inc.1653-01-2003.

[6] X. Hua and D. W. Herrin. Practical Considerations when using the Two-Load Method to Determine the Transmission Loss of Mufflers and Silencers. *SAE International*, 2013.

[7] R. Glav, M. Abom and R. Fairbrother. Acoustic modeling for practical intake and exhaust system design. *4th International styrian noise, vibration and harshness congress*, 2006.

[8] A. Hynninen, R. Turunen, M. Åbom, and H. Bodén. Acoustic Source Data for Medium Speed IC-Engines. ASME. *J. Vib. Acoust*. doi:10.1115/1.4006415, 2012.

[9] M. L. Munjal. Recent Advances in Muffler Acoustics. *International Journal of Acoustics and Vibration*, Vol. 18, No. 2, 2013.

[10] T. Elnady, M. Abom and S. Allam. Modeling perforates in mufflers using two-ports, *ASME Journal of Vibration and Acoustics*, 132, 2010, pp 1–11.

[11] A. Mimani and M. L Munjal. Transverse plane wave analysis of short elliptical chamber mufflers — An analytical approach, *Journal of Sound and Vibration*, 330, 2011, pp 1472–1489.

[12] BOOST Version 5.0.2, AVL LIST GmbH, Graz, Austria, 2007.

[13] Y. Gerges, R. Jordan, A. Thieme, L. Coelho and P. Arenas. Muffler modeling by transfer matrix method and experimental verification. Journal of the Brazilian. *Society of Mechanical Sciences and Engineering*, Vol. 27, No. 2, 2005, pp 132-140.

[14] Y Sathyanarayana and M. L. Munjal. Hybrid approach for aeroacoustic analysis of the engine exhaust system. *Applied Acoustics*. 60, 2000, pp 425-450.

[15] F. D. Denia, Albelda, F. J.Fuenmayor and A. J. Torregrosa. Acoustic behaviour of elliptical chamber mufflers, *Journal of Sound and Vibration*, Vol. 241, No. 3, 2001, pp 401–421.

[16] B. Ouédraogo, R. Maréchal, J.-M. Ville, and E. Perrey-Debain. Broadband noise reduction by circular multi-cavity mufflers operating in multimodal propagation conditions. *Applied Acoustics*, 107, 2016, pp 19-26.

[17] V. Sagar, M. L. Munjal. Design and analysis of a novel muffler for wide-band transmission loss, low back pressure and reduced flow-induced noise. *Noise Control Engineering Journal* Vol. 64, No. 2, 2016, pp 208-216.

[18] S. Talegaonkar, M. R. B. Agrewale, and K. Vora Chhaganlal. Design and Development of Tunable Exhaust Muffler for Race Car. *SAE Technical Papers International Mobility Conference,* SIIMC 2016.

[19] S.J, Liu, J. J Zeng, W.W. Han, Y. Chen, and J. Wang. Intake and exhaust system performance of diesel engine based on CFD and steady flow test method Neiranji Xuebao/Transactions of CSICE [*Chinese Society for Internal Combustion Engines*] Vol. 34, No. 1, 2016, pp 68-73.

[20] Ji. Zhenlin and Fan Yiliang. MAP: a Simulative Program for Acoustic Prediction and Analysis of Duct Muffling Systems. DOI: 10.4271/2015-01-2317, 2015.

[21] X. Hua, Y. Zhang, and D.W. Herrin. The effect of conical adapters and choice of reference microphone when using the two load method measuring muffler transmission loss. *Applied Acoustics*, Vol. 93, No. 6, 2015, pp 75-87.

[22] Jin Woo Lee. Optimal topology of reactive muffler achieving target transmission loss values: Design and experiment. *Applied Acoustics*, Vol. 88, No. 2, 2015, pp 104-13.

[23] Nishant K. Singh, and Philip A. Rubini. Large Eddy Simulation of acoustic pulse propagation and turbulent flow interaction in expansion mufflers. *Applied Acoustics*, Vol. 98, No. 11, 2015, pp 6-19.

[24] C.J. Wu, X.J. Wang, and H.B. Tang. Transmission loss prediction on a single-inlet/double-outlet cylindrical expansion chamber muffler by using the modal meshing approach. *Applied Acoustics*, Vol. 69, No. 2, 2008, pp 173-178.

[25] Takashi Yasuda, Chaoqun Wu, Noritoshi Nakagawa, and Kazuteru Nagamura. Predictions and experimental studies of the tail pipe noise of an automotive muffler using a one-dimensional CFD model. *Applied Acoustics*, Vol. 71, No. 8, 2010, pp 701-707.

[26] S. Allam, H. Bodén & M. Åbom. Over-Determination in Acoustic Two-Port Data Measurement. *The Thirteenth International Congress on Sound and Vibration*. Vienna-Austria, 2006.

[27] M. L. Munjal. Acoustic Characterization of an Engine Exhaust Source – A Review. *Proceedings of Acoustics*, 2004.