PARAMETRIC STUDIES ON
MUFFLER INTERNAL GEOMETRY RELATED TO
SOUND TRANSMISSION LOSS AND PRESSURE DROP

MAHADHIR BIN MOHAMMAD

UNIVERSITI TEKNOLOGI MALAYSIA

PARAMETRIC STUDIES ON
MUFFLER INTERNAL GEOMETRY RELATED TO
SOUND TRANSMISSION LOSS AND PRESSURE DROP

MAHADHIR BIN MOHAMMAD

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

School of Mechanical Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

OCTOBER 2020

ACKNOWLEDGEMENT

In the Name of Allah, the Most Gracious and the Most Merciful. All praises to the Almighty Allah SWT, with His blessing, I finally completed my master thesis in the given time despite of the challenges. Above all, I would always like to thank my parents, Mohammad Bin Amzah and Sapiah Bte Abd Rahiman and my brother for their support and patience.

In preparing this thesis, I was in contact with many people, researchers, academicians, and practitioners. They have contributed towards my understanding and thoughts. I wish to express my sincere appreciation to my main supervisor, Associate Professor Dr. Mohd Farid Bin Muhamad Said, for encouragement, guidance, critics and friendship. I am also very thankful to my previous superior Ir. Maysnan Bin Hamzah and my current superior Associate Professor Dr Srithar Rajoo for giving me time, guidance, advices and motivation. Without their continued support and interest, this thesis would not have been the same as presented here.

I am also indebted to Universiti Teknologi Malaysia (UTM) for give discount on my tuition fees and provide a conducive environment to conduct research.

My fellow postgraduate student should also be recognised for their support. My sincere appreciation also extends to all my colleagues and others who have helped at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. I am grateful to all my family member.

ABSTRACT

Muffler is a device to attenuate noise generated in the exhaust gas. Based on the current noise regulation, automotive manufacturer was forced to improve the muffler performances. Parametric approached was used to improve the existing muffler performances rather than designing a new muffler. The research aim was to investigate the effect of main muffler internal geometry towards STL and PD across the muffler. A comprehensive parametric study was conducted to analyse the effect of muffler internal geometry towards its performance. Two mufflers were selected in this research work; one simple expansion chamber and the other was a complex muffler 1.6 litre natural aspirated engine. Both mufflers performances were measured experimentally using impedance tube and SuperFlow bench machine. The simple expansion chamber was used to validate the proposed concept of 1D model generated by Ricardo WAVE meanwhile, the complex muffler was used for comprehensive parametric studies to investigate the effect of internal muffler geometry towards STL and PD using the 1D model. Four parameters were examined, namely main shell volume, pipe diameter, perforated baffle and perforated pipe. The effect of internal geometry was analysed from the parametric studies. When the muffler volume was increased, the average STL was increased and the PD was reduced, respectively. When the diameter of the pipe was increased, the average STL and PD were dropped. The perforated on baffle showed less effect on average STL where it can increase by a maximum of 1 dB. However, the PD showed a reduction trends as the perforated on baffle was increased. The perforated on pipe shows major effect at 600 Hz only and PD reduced as the perforated on pipe was increased. From the parametric studies, the STL was mostly affected by the muffler main volume while PD was affected by the pipe diameter. In order to minimise the PD, the perforated was introduced to the muffler design. Adding a resonator and increasing the baffle spacing help to improve the muffler performances. As a result, the complex muffler was successfully optimised with an increase in average STL by 3.59% and maintained the PD.

ABSTRAK

Peredam bunyi (PB) adalah sebuah peranti bagi mengurangkan bunyi yang terhasil dari pelepasan gas ekzos. Berdasarkan kepada peraturan bunyi semasa, pengeluar automotif telah di sarankan untuk menambahbaik prestasi PB. Pendekatan parametrik telah digunakan untuk menambahbaik prestasi PB sedia ada berbanding dengan mereka bentuk PB yang baharu. Tujuan penyelidikan ini adalah untuk mengkaji kesan dalaman geometri utama PB terhadap kehilangan penghantaran bunyi (KPB) dan susutan tekanan (ST) PB. Kajian parametrik yang komprehensif telah dilakukan dalam menganalisis kesan geometri dalaman PB terhadap prestasinya. Dua buah PB telah dipilih di dalam kajian penyelidikan ini; satu kebuk pengembangan mudah (KPM) manakala satu lagi adalah peredam bunyi kompleks (PBK) 1.6 liter enjin sedutan semulajadi. Prestasi kedua-dua PB ini di ukur secara uji kaji menggunakan tiub galangan dan mesin meja SuperAliran. KPM telah digunakan untuk mengsahihkan konsep model 1D yang dihasilkan oleh Ricardo Wave manakala PBK digunakan untuk kajian kesuluruhan parametrik bagi mengkaji kesan geometri dalaman PBK terhadap KPB dan PD menggunakan model 1D. Empat parameter telah dikaji iaitu isipadu kelompang utama, garis pusat paip, sesekat tertebuk dan paip tertebuk. Kesan geometri dalaman telah dianalisis dari kajian parametrik. Bila isipadu PB meningkat, purata KPB meningkat dan ST berkurang. Bila garis rentas paip meningkat, purata KPB dan ST menurun. Prestasi sesekat tertebuk menunjukkan kesan yang kurang terhadap purata KPB dengan peningkatan maksimum sebanyak 1 dB sahaja. Walaubagaimanapun, ST menunjukkan tren penurunan apabila tertebuk pada sesekat meningkat. Paip tertebuk menunjukkan kesan yang besar pada 600 Hz sahaja, dan ST berkurang apabila tertebuk pada paip meningkat. Dari kajian parametrik, KPB banyak dipengaruhi oleh isipadu utama PB manakala ST pula dipengaruhi oleh garis pusat paip. Untuk meminimumkan ST, tebukan telah diperkenalkan kepada reka bentuk PB. Dengan menambah penyalun dan meningkatkan jarak sesekat, dapat membantu memperbaiki prestasi PB. Hasilnya, PBK telah berjaya dioptimumkan dengan peningkatan purata KPB sebanyak 3.59% dengan mengekalkan ST.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

1D	One-dimensional
3D	Three-dimensional
BP	Back pressure
CFM	Cubic feet per minute
CID	Cubic inch displacement
DAQ	Data acquisition system
EU	European Union
IL	Insertion loss
ITM	Integrated transfer matrix
NA	Natural aspirated
PD	Pressure drop
PLC	Pressure loss coefficient
RPM	Revolution per minutes
SPL	Sound pressure level
STL	Sound transmission loss
TL	Transmission loss
VE	Volumetric efficiencies

LIST OF SYMBOLS

$\|H^c\|$	Amplitude
m	Area ratio
H^c	Correction transfer function
dB	Decibels
ΔP	Delta pressure
ρ	Density
H^I	Direct transfer function
R	Gas constant
γ	Heat capacity ratio
M_c	Mach number
$\dot{m}$	Mass flow rate
s_1, s_2	Microphone spacing
L, d	Muffler length
k	Natural frequency
φ^c	Phase mismatches
P	Pressure
ξ	Pressure loss coefficient
c	Speed of sound
H^{II}	Switched transfer function
T	Temperature
$T_{11,}$	Transfer matrix
TL	Transmission loss
d	Tube diameter
f_u	Upper frequency
V	Volume

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background Study

The muffler is a device used to attenuate noise generated from the engine. The noise generated from the engine is transmitted through the exhaust gas. Along the exhaust gas path, the gas will meet up the muffler. As a result, the noise energy carry in the gases is attenuated.

Muffler divided into two types which are the reactive muffler and dissipative muffler. The reactive muffler mechanism operates by using the wave cancelation between the incident wave and the reflected wave. Thus, the positive wave and negative wave hit opposite and create noise cancelation effect. The dissipative muffler mechanism is based on the absorptive principle. The softer the material, more sound are absorbed and attenuate.

To create noise cancelation, the internal geometry of the muffler plays a big role. The internal geometry of the muffler consists of the volume of the chamber, shape of the chamber, inlet and outlet diameter, porosity of the perforated type, baffle spacing and baffle number.

A muffler with a various internal geometry also knows as complex muffler. Complex muffler defined as the muffler with a various geometry inside the muffler such as baffle plate, extended pipe, bend pipe, perforated pipe, perforated pipe, unique perforated arrangement and come with resonator.

The muffler performance commonly measured based on two parameter which are sound transmission loss (STL) and pressure drop (PD). To determine the muffler performances, all the parameter can be determined theoretically, experimentally and computer simulation.

1.2 Problem Statement

Muffler is a device to attenuate noise generated in exhaust stream. With the current enhanced and stringent noise regulation by the country like Japan and organization such as European Union have forced the automotive manufacturer to improve the muffler noise absorption. While having a better muffler noise absorption, the pressure drop of the muffler must be maintained because the engine performances cannot be compromised. Furthermore, the noise generated from the exhaust can provide a low ride comfort and lead stress to the driver especially the low frequency noise. Despite of having a newly design muffler, improving the existing muffler model by modified the internal muffler geometry can produce a good muffler sound absorption and maintain the pressure drop. Identifying a specific parameter through parametric study on the internal geometry study with major effect towards sound absorption and pressure drop can help the automotive manufacture to improve the existing muffler design. Moreover, the current technique used by some of automotive manufacturer are try and error method to get the results.

Parametric studies can be conducted through a simulation process that save a lot of money and time. One of the important approaches is 1D modelling and 3D modelling. Instead of using a 3D modelling tools that is time consuming, 1D modelling are more convenient with less time taken and with acceptable accuracy. Hence, this study focuses to identify the muffler internal geometry effect through parametric study and with the finding from the parametric studies, the result was used a guideline to improve the muffler performances by using a 1D simulations. One complex muffler for current commercial muffler had been selected for this study. This muffler was chosen because of the internal geometry less complexity compare to another commercial muffler that are more complex than the selected muffler.

1.3 Research Objectives

The objectives of the research are:

i. To determine the current exhaust muffler sound transmission loss and pressure drop using 1D simulation and experiment.

ii. To analyse the effect of exhaust muffler internal geometries toward the sound transmission loss and pressure drop.

iii. To optimise the current exhaust muffler model by increasing sound transmission loss at least 3% and maintain the pressure drop.

1.4 Research Significant

The research will be conducted based on the problem statement described in Section 1.2. The new proposed muffler design will have a better sound transmission loss (sound absorption) and maintain the pressure drop. The findings from this research work can become references for the vehicle manufacturer to improve their muffler performances with the existing muffler design. The method used in this research will be discussed briefly and comprehensive parametric studies were conducted. Finding from the parametric studies were used as guideline to improve the existing muffler design. Understand effect of internal arrangement is a critical aspect that will lead to a better acoustic design. Combination of different internal configurations can provide benefits to automotive manufacturer.

Parametric studies will run using a 1D simulations tools. The 1D tools were choose because it saves time with acceptable accuracy. Furthermore, the engine simulation also was done in 1D simulation. By doing this, it can help the automotive manufacturer to improve their existing muffler design with a minimal cost and save a lot of time. Furthermore, this study filled the gap between the 1D and 3D analysis of sound transmission loss and pressure drop.

1.5 Research Scope

i. Two specimens used, simple expansion chamber and complex muffler.

ii. The simple expansion chamber was design to be use as 1D model validation before proceeded with complex muffler.

iii. The muffler model used for parametric studies was a complex muffler 1.6 Liter natural aspirated (NA) engine.

iv. Validation of simple expansion chamber and complex muffler performances between 1D simulation and experiment at frequency below 1000 Hz.

v. The research focused on the main exhaust muffler and four parameters of internal geometry; volume, pipe diameter, perforated baffle and perforated pipe.

vi. The studied performances consist of sound transmission loss (STL) and pressure drop (PD)

REFERENCES

[1] Olt J, Mikita V, Roots J, et al. Cylinder Pressure Characteristics of Turbocharged and Naturally Aspirated Diesel Engines. *Procedia Engineering* 2015; 100: 350–359.

[2] Foster DE, Crolla D, Kobayashi T, et al. *Encyclopedia of Automotive Engineering*. Wiley, https://books.google.com.my/books?id=TT88jwEACAAJ (2014).

[3] Åbom M, Kabral R. Turbocharger Noise - Generation and Control. Epub ahead of print 2014. DOI: 10.4271/2014-36-0802.

[4] Kuang X, Pang J, Zhang H, et al. Surge Noise Identification and Control of Automotive Turbochargers. Epub ahead of print 2014. DOI: 10.4271/2014-01-2053.

[5] KENJI HTIST. *Variable valve timing control device*. JP20130192, Japan, 2013.

[6] Nitin Dewangan M anawat. CFD Investigation of Exhaust Gas Bypass on Trolley Heating. *Thermal Management Systems Conference 2020*; 2020-28–00, https://www.sae.org/publications/technical-papers/content/2020-28-0006/ (2020).

[7] Siqueira Mazzaro R, de Morais Hanriot S, Jorge Amorim R, et al. Numerical analysis of the air flow in internal combustion engine intake ducts using Herschel-Quincke tubes. *Applied Acoustics* 2020; 165: 107310.

[8] Novak C, Ule H, Gaspar R. Noise Cancellation Technique for Automotive Intake Noise Using A Manifold Bridging Technique. Epub ahead of print 2005. DOI: 10.4271/2005-01-2368.

[9] Ih J-G, Choi C-Y, Kim T-K, et al. Optimal design of the exhaust system layout to suppress the discharge noise from an idling engine. *International Journal of Automotive Technology* 2011; 12: 617–630.

[10] Qiu S, Yuan Z cheng, Fan R xun, et al. Effects of exhaust manifold with different structures on sound order distribution in exhaust system of four-cylinder engine. *Applied Acoustics* 2019; 145: 176–183.

[11] Deng X, Chen Z, Wang X, et al. Exhaust noise, performance and emission

characteristics of spark ignition engine fuelled with pure gasoline and hydrous ethanol gasoline blends. *Case Studies in Thermal Engineering* 2018; 12: 55–63.

[12] Pinzi S, Redel-Macías MD, Leiva-Candia DE, et al. Influence of ethanol/diesel fuel and propanol/diesel fuel blends over exhaust and noise emissions. *Energy Procedia* 2017; 142: 849–854.

[13] Deng Y, Liu C, Chu P. Research on Integration of Automotive Exhaust-Based Thermoelectric Generator with Front Muffler. Epub ahead of print 2016. DOI: 10.4271/2016-01-0203.

[14] He ZC, Qiu Y, Li E, et al. Analysis on loudness of exhaust noise and improvement of exhaust system based on structure-loudness model. *Applied Acoustics* 2019; 150: 104–112.

[15] Lee D, Perot F, Ih K-D, et al. Prediction of Flow-Induced Noise of Automotive HVAC Systems. Epub ahead of print 2011. DOI: 10.4271/2011-01-0493.

[16] Bennouna S, Matharan T, Cheriaux O. Automotive HVAC Noise Reduction. Epub ahead of print 2018. DOI: 10.4271/2018-01-1519.

[17] Munjal ML. Advances in the acoustics of flow ducts and mufflers. *Sadhana* 1990; 15: 57.

[18] Mishra PC, Kar SK, Mishra H, et al. Modeling for combined effect of muffler geometry modification and blended fuel use on exhaust performance of a four stroke engine: A computational fluid dynamics approach. *Applied Thermal Engineering* 2016; 108: 1105–1118.

[19] Vijayasree NKK, Munjal MLL. On an Integrated Transfer Matrix method for multiply connected mufflers. *Journal of Sound and Vibration* 2012; 331: 1926–1938.

[20] Das B, Verma PK, Thukaram D, et al. Optimal topology of reactive muffler achieving target transmission loss values: Design and experiment. *Applied Acoustics* 2015; 69: 104–113.

[21] Biswas S, Mandal G. An Approach to Reduce the Product Variants through Design of Hybrid Muffler for Commercial Vehicle Application. Epub ahead of print 2013. DOI: 10.4271/2013-26-0096.

[22] Bobby Kimbrough. Understanding Muffler Design and Sound Absorption Strategies - Street Muscle. *Street Muscle Magazine*, 2014,

http://www.streetmusclemag.com/tech-stories/exhaust/understanding-muffler-design-and-sound-absorption-strategies/ (2014, accessed 13 July 2018).

[23] Zhu Y, Zhu F, Zhang Y, et al. The research on semi-active muffler device of controlling the exhaust pipe's low-frequency noise. *Applied Acoustics* 2017; 116: 9–13.

[24] High performances glass pack muffler, https://www.holley.com/products/exhaust/mufflers/absorption_glass_pack_mufflers/red_hots/ (accessed 31 January 2019).

[25] Yu X, Cheng L. Duct noise attenuation using reactive silencer with various internal configurations. *Journal of Sound and Vibration* 2015; 335: 229–244.

[26] Selamet A, Radavich PM. The effect of length on the acoustic attenuation performance of concentric expansion chambers: An analytical, computational and experimental investigation. *Journal of Sound and Vibration* 1997; 201: 407–426.

[27] Fan W, Guo LX. An Investigation of Acoustic Attenuation Performance of Silencers with Mean Flow Based on Three-Dimensional Numerical Simulation. *Shock and Vibration*; 2016. Epub ahead of print 2016. DOI: 10.1155/2016/6797593.

[28] Middelberg JM, Barber TJ, Leong SS, et al. CFD analysis of the acoustic and mean flow performance of simple expansion chamber mufflers. In: *American Society of Mechanical Engineers, Noise Control and Acoustics Division (Publication) NCA*. 2004, pp. 151–156.

[29] Xiang L, Zuo S, Wu X, et al. Study of multi-chamber micro-perforated muffler with adjustable transmission loss. *Applied Acoustics* 2017; 122: 35–40.

[30] Kheybari M, Ebrahimi-Nejad S. Locally resonant stop band acoustic metamaterial muffler with tuned resonance frequency range. *Materials Research Express* 2018; 6: 25802.

[31] Lu H, Wu T, Bai S, et al. Experiment on thermal uniformity and pressure drop of exhaust heat exchanger for automotive thermoelectric generator. *Energy* 2013; 54: 372–377.

[32] Kim S, Cheong C, Park J, et al. Étude des performances acoustique et d'écoulement de silencieux d'aspiration dans un compresseur hermétique à piston. *International Journal of Refrigeration* 2016; 69: 74–84.

[33] Elsayed A, Bastien C, Jones S, et al. Investigation of baffle configuration effect on the performance of exhaust mufflers. *Case Studies in Thermal Engineering* 2017; 10: 86–94.

[34] Chen Z, Ji Z, Huang H. Acoustic impedance of perforated plates in the presence of bias flow. *Journal of Sound and Vibration* 2019; 446: 159–175.

[35] Munjal ML, Krishnan S, Reddy MM. Flow-acoustic performance of perforated element mufflers with application to design. *Noise Control Engineering Journal* 1993; 40: 159–167.

[36] Yedeg EL, Wadbro E, Berggren M. Interior layout topology optimization of a reactive muffler. *Structural and Multidisciplinary Optimization* 2016; 53: 645–656.

[37] Munjal ML. *Acoustics of Ducts and Mufflers With Application to Exhaust and Ventilation System Design*. Canada: John Wiley & Sons, https://books.google.com.my/books?id=Z-s50vk-U68C&lr=&source=gbs_navlinks_s (1987).

[38] Chiu M-C. Shape optimization of multi-chamber mufflers with plug-inlet tube on a venting process by genetic algorithms. *Applied Acoustics* 2010; 71: 495–505.

[39] Panigrahi SN, Munjal ML. Backpressure considerations in designing of cross flow perforated-element reactive silencers. *Noise Control Engineering Journal* 2007; 55: 504–515.

[40] Shi X, Mak C-M. Sound attenuation of a periodic array of micro-perforated tube mufflers. *Applied Acoustics* 2017; 115: 15–22.

[41] Shen C, Hou L. Comparison of various algorithms for improving acoustic attenuation performance and flow characteristic of reactive mufflers. *Applied Acoustics* 2017; 116: 291–296.

[42] Tao Z, Seybert AF. A Review of Current Techniques for Measuring Muffler Transmission Loss. *SAE Transactions* 2003; 112: 2096–2100.

[43] Soo Jung S, Tae Kim Y, Bong Lee Y. Measurement of Sound Transmission Loss by Using Impedance Tubes. *Journal of the Korean Physical Society* 2008; 53: 596–600.

[44] Jena DPP, Panigrahi SNN. Numerically estimating acoustic transmission loss of a reactive muffler with and without mean flow. *Measurement* 2017; 109: 168–186.

[45] Ichiyanagi T, Kuribayashi T, Nishiumi T. Investigations on Wave Propagation of the Pressure Pulsation in a Helmholtz-type Hydraulic Silencer with a Hemispherical Vessel. *Journal of Vibration and Acoustics*; 139. Epub ahead of print 2016. DOI: 10.1115/1.4034618.

[46] Munjal ML. Analysis and design of mufflers—an overview of research at the Indian institute of science. *Journal of Sound and Vibration* 1998; 211: 425–433.

[47] Xu J, Zhou S, Li K. Analysis of flow field and pressure loss for fork truck muffler based on the finite volume method. *International Journal of Heat and Technology* 2015; 33: 85–90.

[48] Massey S, Williamson PS, Chuter RJ. Modelling exhaust systems using one-dimensional methods. *SAE Technical Papers*. Epub ahead of print 2002. DOI: 10.4271/2002-01-0005.

[49] Om Ariara Guhan CP, Arthanareeswaren G, Varadarajan KN. CFD Study on Pressure Drop and Uniformity Index of Three Cylinder LCV Exhaust System. In: *Procedia Engineering*. 2015, pp. 1211–1218.

[50] Elnady T, Åbom M. SIDLAB: new 1D sound propagation simulation software for complex duct networks. *13th International Congress on Sound and Vibration* 2006; 2–6.

[51] Mohammad M, Buang MMA, Dahlan AA, et al. Simulation of automotive exhaust muffler for tail pipe noise reduction. *Jurnal Teknologi*; 79. Epub ahead of print 2017. DOI: 10.11113/jt.v79.12263.

[52] Chen Y, Lv L. Design and evaluation of an Integrated SCR and exhaust Muffler from marine diesels. *Journal of Marine Science and Technology (Japan)* 2015; 20: 505–519.

[53] Andersen K. Analyzing muffler performance using the transfer matrix method. *Proceedings of the COMSOL Conference 2008 …*, http://static3.comsol.nl/papers/5079/download/Andersen.pdf (2008).

[54] Guhan CPOA, Arthanareeswaran G, Varadarajan KN, et al. Exhaust System Muffler Volume Optimization of Light Commercial Vehicle Using CFD Simulation. In: *Materials Today: Proceedings*. Elsevier, pp. 8471–8479.

[55] Jeon S, Kim D, Hong C, et al. Acoustic performance of industrial mufflers with CAE modeling and simulation. *International Journal of Naval Architecture and Ocean Engineering* 2014; 6: 935–946.

[56] Sagar V, Munjal ML. Analysis and design guidelines for fork muffler with H-connection. *Applied Acoustics* 2017; 125: 49–58.

[57] Ji Z, Fang Z. Three-pass Perforated Tube Muffler with End-resonator. *SAE Int J Passeng Cars – Mech Syst* 2011; 4: 989–999.

[58] Selamet A, Ji ZL. Acoustic Attenuation Performance of Circular Expansion Chambers With Extended Inlet/Outlet. *Journal of Sound and Vibration* 1999; 223: 197–212.

[59] Ih J, Lee B. Analysis of higher-order mode effects in the circular expansion chamber with mean flow. *The Journal of the Acoustical Society of America* 1985; 77: 1377–1388.

[60] Yasuda T, Wu C, Nakagawa N, et al. Predictions and experimental studies of the tail pipe noise of an automotive muffler using a one dimensional CFD model. *Applied Acoustics* 2010; 71: 701–707.

[61] Ji Z, Ma Q, Zhang Z. Application of the boundary element method to predicting acoustic performance of expansion chamber mufflers with mean flow. *Journal of Sound and Vibration* 1994; 173: 57–71.

[62] Herrin DW, Hua X, Zhang Y, et al. The Proper Use of Plane Wave Models for Muffler Design. *SAE Int J Passeng Cars - Mech Syst* 2014; 7: 927–932.

[63] Neihguk D, Munjal ML, Ram A, et al. Acoustic Analysis of a Compact Muffler for Automotive Application. *SAE Int J Veh Dyn, Stab, and NVH* 2017; 1: 97–111.

[64] Siano D, Auriemma PhD F, Bozza F, et al. Validation of 1D and 3D Analyses for Performance Prediction of an Automotive Silencer. Epub ahead of print 2011. DOI: 10.4271/2011-24-0217.

[65] Vishwakarma A, Chandramouli P, Ganesan V. Acoustic Analysis of Exhaust Muffler of a 4-Stroke Engine. *SAE Int J Passeng Cars – Mech Syst* 2009; 2: 1303–1311.

[66] Amphlett S, Niven PC, Payri F, et al. Linear Acoustic Modelling using 1-D Flow Systems which represent Complex 3-D Components. Epub ahead of print 2011. DOI: 10.4271/2011-01-1524.

[67] Siano D. Three-dimensional/one-dimensional numerical correlation study of a three-pass perforated tube. *Simulation Modelling Practice and Theory* 2011; 19: 1143–1153.

[68] Barbieri R, Barbieri N. Finite element acoustic simulation based shape

optimization of a muffler. *Applied Acoustics* 2006; 67: 346–357.

[69] Wu C-H, Wang C-N. Attenuation for the Simple Expansion Chamber Muffler with a Right Angle Inlet. *Journal of Mechanics*; 27. Epub ahead of print 1 September 2011. DOI: 10.1017/jmech.2011.19.

[70] Zheng F, Li J, Van Zuylen H, et al. Influence of driver characteristics on emissions and fuel consumption. In: *Transportation Research Procedia*. Elsevier, pp. 624–631.

[71] Davis, Don D J, Stokes GM, Moore D, et al. *Theoretical and Experimental Investigation of Mufflers with Comments on Engine-Exhaust Muffler Design*, https://ntrs.nasa.gov/search.jsp?R=19930092208 (1954).

[72] ASTM International. ASTM E2611-09: Standard Test Method for Measurement of Normal Incidence Sound Transmission of Acoustical Materials Based on the Transfer Matrix Method. 2009.

[73] Hua X, Herrin D. *Practical Considerations when using the Two-Load Method to Determine the Transmission Loss of Mufflers and Silencers*. 2013. Epub ahead of print 20 May 2013. DOI: 10.4271/2013-01-1881.

[74] Chung JY, Blaser DA. Transfer function method of measuring in-duct acoustic properties. I. Theory. *The Journal of the Acoustical Society of America* 1980; 68: 907–913.

[75] Dahlan AA, Shahrafi M, Muhamad Said MF. Simulation of intake and exhaust valve timing on internal combustion engine. *Jurnal Teknologi* 2017; 79: 47–52.

[76] Kim HS, Ma PS, Kim SR, et al. A model for the sound absorption coefficient of multi-layered elastic micro-perforated plates. *Journal of Sound and Vibration* 2018; 430: 75–92.

[77] Lee JW. Optimal topology of reactive muffler achieving target transmission loss values: Design and experiment. *Applied Acoustics* 2015; 88: 104–113.

LIST OF PUBLICATIONS

Mohammad, M., Buang, M. M. A., Dahlan, A. A., Khairuddin, M. H., & Muhamad Said, M. F. (2017). Simulation of automotive exhaust muffler for tail pipe noise reduction. *Jurnal Teknologi*, *79*(7–4), 37–45. https://doi.org/10.11113/jt.v79.12263

Mohammad, M., Muhamad Said, M. F., Khairuddin, M. H., A Kadir, M. K., Dahlan, M. A. A., & Zaw, T. (2019). Complex geometry automotive muffler sound transmission loss measurement by experimental method and 1D simulation correlation. *Sustainable & Integrated Engineering Coference 2019*, Putrajaya