UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Mechanical Engineering

INVESTIGATION ON THE SOUND TRANSMISSION LOSS OF DOOR SEALING SYSTEM USING HYBRID FE-SEA METHOD

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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Master of Science in Mechanical Engineering

2021

INVESTIGATION ON THE SOUND TRANSMISSION LOSS OF DOOR SEALING SYSTEM USING HYBRID FE-SEA METHOD

NORZAILAN BIN AZAHARI

A thesis submitted
in fulfillment of the requirements for the degree of Master of Science
in Mechanical Engineering

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2021

DECLARATION

I declare that this thesis entitled "Investigation on the Sound Transmission Loss of Door Sealing System using Hybrid FE-SEA Method" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not currently submitted in candidature of any other degree.

Signature : .....

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Date : 26 /3 /2021

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APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering.

Signature : .....

Supervisor Name : Assoc. Prof. Dr. Azma Putra

Date : 26 MARCH 2021

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DEDICATION

To my beloved family.

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ABSTRACT

Vehicle door seals which are located around the car doors play a major role in determining the isolation of the passenger cabin from wind noise and water. The door seals are made from foamed rubber materials so that they can deform into different mating surfaces. As the vehicle is driven at high speeds, turbulence noise from the door seal becomes apparent and the wind noise becomes the primary noise generated into the vehicle interior through the slits or channels on the automotive door surface. The quality of the seals then determines the contribution of the noise level in the cabin. Despite various studies conducted on sound transmission loss (STL) of the door sealing system, the study on modelling the STL using three-dimensional (3D) model is still not well established, especially for a double-seal type. Modelling accurate transmission loss of the seal is still a challenging task and thus this becomes the main objective of this study. The method employs the 3D hybrid Finite Element and Statistical Energy Analysis (FE-SEA) to model the double-seal system and the air channel around the seal using VA-One software. The hybrid model was validated using experimental data from measurement in a diffuse field environment. The result reveals a fairly good agreement between the simulation and experiment with variability of 3 - 10 dB above 1 kHz. The parametric study is then conducted to observe the effect of the thickness, type of material, density, elastic modulus, damping and the cavity size between the frame and door seal on the STL. Especially for the latter, it is revealed that by additional of 2 mm spacing between both seals, the STL can be improved by almost 10 dB above 2 kHz. The comparison of single and double-seal shows that double-seal has significantly greater STL compared to the single seal by 10 - 30 dB at the mass law region above 1 kHz.

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PENYIASATAN KEHILANGAN TRANSMISI BUNYI PADA SISTEM KEDAPAN PINTU KERETA MENGGUNAKAN HIBRID FE-SEA

ABSTRAK

Pengedap pintu kenderaan yang terletak di sekitar pintu kereta memainkan peranan utama dalam menentukan pengasingan kabin penumpang dari bunyi angin dan air. Sebilangan besar pengedap pintu dibuat dari bahan getah sehingga boleh berubah menjadi bentuk permukaan yang berbeza. Apabila kenderaan digerakkan dengan kelajuan yang tinggi, bunyi turbulensi dari pengedap pintu menjadi jelas dan bunyi angin menjadi bunyi utama yang dihasilkan dan menyebarkan ke kabin dalaman kenderaan melalui celah atau saluran di permukaan pintu automotif. Kualiti pengedap pintu akan menentukan tahap kebisingan dan keselsesaan di dalam kabin kenderaan. Walaupun terdapat pelbagai kajian yang dilakukan mengenai prestasi penebat bunyi (kehilangan transmisi) sistem pengedap pintu, kajian tentang pemodelan kehilangan transmisi menggunakan model tiga dimensi (3D) masih belum mapan, terutama untuk jenis kedap pintu jenis dua-pengedap. Memodelkan kehilangan penghantaran pengedap pintu yang tepat masih merupakan tugas yang mencabar dan disebabkan itu ia menjadi objektif utama kajian ini. Kaedah ini menggunakan model hibrid 3D dan Analisis Tenaga Statistik (FE-SEA) pengedap pintu berkembar dan saluran udara di sekitar pengedap pintu menggunakan perisian VA-One. Model hibrid ini kemudian disahkan menggunakan data eksperimen daripada pengukuran di persekitaran medan yang tersebar. Keputusan ujian menunjukkan kesepakatan yang cukup baik antara simulasi dan eksperimen dengan perbezaan di antara 3 - 10 dB untuk frekuensi di atas 1 kHz. Kajian parametrik kemudian dijalankan untuk melihat kesan ketebalan, jenis bahan, ketumpatan, modulus elastik, redaman dan saiz rongga antara pengedap bingkai dan penutup pintu terhadap STL. Khusus untuk masa akan datang, terbukti bahawa dengan penambahan jarak 2 mm di antara kedua-dua pengedap pintu, STL dapat ditingkatkan hampir 10 dB untuk frekuensi di atas 2 kHz. Perbandingan pengedap pintu tunggal dan dua pengedap pintu menunjukkan bahawa dua pengedap pintu mempunyai STL yang jauh lebih besar berbanding dengan pengedap pintu tunggal sebanyak 10 - 30 dB di kawasan hukum jisim di atas 1 kHz.

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ACKNOWLEDGEMENTS

It is a great pleasure to acknowledge my sincere thanks and gratitude to my supervisor, Assoc. Prof. Dr. Azma Putra for suggesting the topic of this research. It is definitely a great honour to work under his supervision and guidance, the opportunities given and the experiences gained are invaluable. Also, the assistance from Mr. Muhammad Nur Othman, lecturer from Faculty of Engineering Technology, UTeM is very much appreciated. This includes Mr. Johardi Bin Abdul Jabar, the laboratory assistant of Vibro-acoustic laboratory. Experimental works would not be done smoothly without their helps. Appreciation is also addressed to ESI Group for the educational version of the VA-One software. I would like to acknowledge Ministry of Education (MOE) and especially Universiti Teknikal Malaysia Melaka (UTeM) for appointing me as Graduate Research Assistant (GRA) and for supporting my monthly allowance. Most important recognition and appreciation are dedicated to my family who supported me in the joys and frustrations during my study. My greatest praise is reserved for my wife, Nor Hafizah Hussin. I appreciate her admirable patience, understanding and encouragement, which helped immensely in sustaining my efforts especially during the writing of this thesis.

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LIST OF ABBREVIATIONS

2D	–	2 Dimensional
3D	–	3 Dimensional
ASTM	–	American Standard Test Method
CLD	–	Compression Load Deflection
CLF	–	Coupling Loss Factor
DAF	–	Diffuse Acoustic Field
DLF	–	Damping Loss Factor
EPDM	–	Ethylene Propylene Diene Monomer
FE	–	Finite Element
FEA	–	Finite Element Analysis
FEM	–	Finite Element Method
FE-SEA	–	Finite Element –Statistical Energy Analysis
FSI	–	Fluid-Structural Interaction
ISO	–	International Organisation of Standard
NVH	–	Noise Vibration and Harshness
R&D	–	Research and Development

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RMS	–	Root Mean Square
SEA	–	Statistical Energy Analysis
SIF	–	Semi Infinite Fluid
SPL	–	Sound Pressure Level
STL	–	Sound Transmission Loss
TL	–	Transmission Loss
TPV	–	Thermoplastic Vulcanizates

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LIST OF SYMBOLS

a & b	–	Panel dimensions
c	–	Speed of sound
D	–	Bending stiffness
E	–	Young modulus or Tensile modulus or Elastic modulus)
f	–	Frequency
H	–	Distance of frame panel surface and the door panel surface
H_0	–	Initial distance of frame panel surface and the door panel surface
i, n	–	Integers
I	–	Sound intensity
I_0	–	Reference sound intensity (10^{-12} W/m^2)
I_i & I_1	–	Incident sound intensity
I_t & I_2	–	Transmitted sound intensity
$Im(G_{12})$	–	Imaginary part of the cross-spectrum from the probe
L_p	–	Sound pressure level
L_w	–	Sound power level
m	–	Mass per unit area

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p	–	Sound pressure
p_0 & p_{ref}	–	Reference sound pressure (2x10^{-5})
$< \bar{p_1^2} >$	–	Spatially mean square pressure
S_1	–	Area of test specimen
S_2	–	Area of measurement surface
W	–	Sound power
W_a	–	Absorb sound power
W_i & W_1	–	Incident sound power
W_t & W_2	–	Transmitted sound power
W_r	–	Reflected sound power
λ	–	Wavelength
ρ	–	Density
ω	–	Angular frequency
τ	–	Transmission coefficient
θ	–	Angle of incidence
ν	–	Poisson's ratio
η_D	–	Damping loss factor
Δr	–	Distance between the surface of the two closely spaced microphone of the probe
Π_D	–	Power dissipated by damping in a band of frequencies

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LIST OF PUBLICATIONS

Journal Article

Azahari, N., Putra, A., Dan, R.M. and Othman, M.N.,2019. Sound Insulation Performance of Kenaf Fiber as a Noise Control Treatment in Car Using Statistical Energy Analysis. *Defence S and T Technical Bulletin (STRIDE)*, 12(1), pp. 136-149.

Proceedings

Azahari, N., Putra, A., Dan, R.M. and Othman, M.N.,2018. Modelling Sound Transmission Loss of Car Door Seal Using Hybrid Finite Element and Statistical Energy Analysis, *Proceedings of the International Conference on Progress in Automotive Technology 2018 (ICPAT 2018).*

Azahari, N., Putra, A., Dan, R.M. and Othman, M.N.,2018. Analysis of Sound Transmission Loss (STL) of Kenaf Fibre as a Noise Control Treatment (NCT) using Statistical Energy Analysis (SEA) Method, *Proceedings of the 6th International Conference on Noise, Vibration and Comfort 2018 (NVC 2018).*

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