DESIGN OPTIMIZATION OF THE INTERIOR VEHICLE NOISE AND VIBRATION THROUGH COMPUTATIONAL APPROACHES

by

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LIST OF ABBREVIATIONS

NII	Noise Isolation Index
MLR	Multiple Linear Regression
GA	Genetic Algorithm
RPM	Revolutions Per Minute
BSS	Blind Sources Separation
SVM-GA	Support Vector Machine- Genetic Algorithm
BPNN	Back Propagation Neural Network
PLS	Partial Least Square
CPX	Close Proximity
SPL	Sound Pressure Level
VACI	Vehicle Acoustical Comfort Index
WT	Wavelet Transform
DWT	Discrete Wavelet Transform
SMWVD	Sound Metric based on the Wigner-Ville Distribution
BS-6841,1987	British Standard (Guide to measurement of vibration)
IOS-2631,1997	International Organization for Standardization
RMS	Root Mean Square
PSO-NN	Particle Swarm Optimization Neural Network
ANN	Artificial Neural Network
LSSVM	Least Square Support Vector Machine
GA-SVM	Genetic Algorithm Optimized Support Vector Machine
WPSE	Wavelet Packet Sample Entropy
WPE	Wavelet Packet Energy
GA-BPNN	Genetic Algorithm-Back Propagation Neural network
PSO	Particle Swarm Optimization
PSO-BPNN	PSO-Back Propagation Neural Network
DBN	Deep Belief Network
CRBM	Continues Restricted Boltz-Man Machine
CRBM-DBN	Continues Restricted Boltz-Man Machine- Deep Belief Networks
WPT	Wavelet Packet Transform
EMD	Empirical Mode Decomposition
KNN	K-Nearest Neighbor

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SVM	Support Vector Machine
GANN	Genetic Algorithm based Neural Network
VDV	Vibration Dose Value
JMP	Johns' Macintosh Project/Product
LDA	Linear Discriminant Analysis
NI	National Instrument
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
cDAQ	Compact Data Acquisition

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LIST OF SYMBOLS

dB	Decibel, unit measurement of sound level
Hz	Hertz, unit measurement of frequency
x	Front to back axis
y	Side to side axis
z	The longitudinal (head to toe) axis
a_x	Vibration magnitude x axis,
a_y	Vibration magnitude in the y axis
a_z	The vibration on the longitudinal axis
$a_{SUM}[m^2]$	The sum of the whole body vibration
a	The acceleration value (m/s^2),
$a(t)$	Acceleration frequency time
T	Time period (in seconds)
L	The sound quality parameter loudness [sone],
c	Constant

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Pengoptimuman Rekabentu Hingar Dan Gegaran Dalam Kenderaan Melalui Pendekatan Berpengiraan

ABSTRAK

Kebolehupayaan hingar dan gegaran merupakan kriteria yang amat diperlukan bagi proses rekabentuk dan validasi bagi kenderaan memandangkan ianya memberi kesan ketara kepada imej pemasaran kenderaan automatif. Matlamat utama bagi kajian ini adalah untuk membuat penilaian dan mengoptimumkan tahap akustik dan gegaran di dalam kabin dalaman kenderaan. Untuk tujuan itu, isyarat hingar dan gegaran diperolehi dengan menggunakan tiga kereta kompak Perodua iaitu Axia, Myvi dan Viva dalam jenis pemanduan yang berkeadaan pegun dan tidak pegun (lebuh raya, jalan turapan dan jalan bandar). Hingar dan gegaran yang diukur dianalisa untuk memperolehi kualiti bunyi dan tahap pendedahan gegaran di dalam kabin. Selain itu, kajian mempersembahkan satu formulasi Index Pengasingan Hingar (IPH) berdasarkan kepada pengkategorian trend-trend kualiti bunyi bagi hingar di dalam dan di luar kereta. IPH dibangunkan, dibandingkan dan ditentusahkan untuk tiga jenis kereta yang diuji dan keputusan menunjukkan bahawa Axia mempunyai keselesaan yang paling tinggi dan kriteria pengasingan yang optimum terhadap hingar dari luar kabin. Selain menjalankan pengelompokan untuk mengelompok dan membandingkan keselesaan dalaman bagi Axia, Myvi dan Viva, kajian membangunkan Algoritma Genetik untuk selanjutnya mengoptimumkan hingar dan gegaran di dalam kabin kenderaan. Keputusan bagi model Algoritma Genetik mendedahkan bahawa amaun hingar di dalam kabin dipengaruhi oleh nilai gegaran yang terdedah. Secara keseluruhannya kajian ini menunjukkan bahawa tahap keselesaan adalah dengan nyatanya dipengaruhi oleh faktor-faktor termasuk jenis permukaan jalan, transmisi enjin dan ciri-ciri rekabentuk kenderaan.

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Design Optimization Of The Interior Vehicle Noise And Vibration Through Computational Approaches

ABSTRACT

Noise and vibration performance is an indispensable criterion in vehicle design and validation processes since it significantly affects the marketing image of automotive vehicles. The primary goal of this study is to assess and optimize the acoustic and vibration levels in the interior vehicle cabin. The study demonstrated experimental design to acquire sound and vibration signals using three local compact Perodua cars namely Axia, Myvi and Viva on idle (stationary) and non-stationary (highway, pavement and urban) driving conditions. The measured sounds and vibrations are analyzed to obtain the sound quality and vibration exposure levels in the interior cabin. Apart from this, the study presents a formulation of Noise Isolation Index (NII) based on categorizing the trends of sound quality into interior and exterior noises. The NII is developed, compared and validated for the three tested cars and the results showed that Axia has the highest comfort and thus optimal isolation criterion toward the exterior noises. Besides conducting clustering to compare the interior comfort of Axia, Myvi and Viva, this study developed Genetic Algorithm to further optimize the noise and vibration in the interior vehicle cabin. The results of GA model revealed that the interior noise is influenced by vibration exposure values in the interior vehicle cabin. Overall findings of this study indicate that the comfort level is factually influenced by factors including type of road surface, engine transmissions and vehicle design characteristics.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Vehicle interior sounds and vibrations are important factors of customer satisfaction and have a decisive influence on the automotive product and its quality impression. Indeed, as automotive products become competitive, customers sort their selection in a discriminating and differentiating way based on the perception of sound quality that the vehicles make (Hanouf, Faris, & Nor, 2015; Nopiah, Junoh, & Ariffin, 2015b; Zhang, Hou, Shen, Shi, & Zhang, 2015).

In the competitive automotive markets, there are various factors which influnce the consumer's preferences when selecting an automtoive car such as fuel consumptions, handling, comfort, safety and cost (Duan, Wang, & Xing, 2015). Recently, it has become imperative to connect customer requirements and vehicle's technical specifications to develop a competitive automotive vehicle with high quality and pleasant sound (Stylidis, Wickman, & Söderberg, 2015). As a consequence, various testing procedures with enhanced tools have been developed to direct and enable car manufacturers to improve the interior vehicle comfort. Undoubtedly, noise and vibration performances are essential parameters during the entire process of vehicle designs (Huang, Li, Lim, & Ding, 2016; Panza, 2015).

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The combination of globalization and increased competition in the automobile marketplaces requires well optimization of vehicle's noise and vibration characteristics to produce pleasant vehicles that match costumer's expectations and to remain competitive (Yoon, Yang, Jeong, Park, & Oh, 2012). In fact, nowadays with advancements in technology and improved socioeconomic conditions, the expectations of customers for a comfortable vehicles have increased leading to stiffer competition among automotive manufacturers. Nonetheless, the future of automotive industries depends on many factors including integrating the new technologies with car's designs, the material choices of the interior structures must be revisited and producing cost effective and sustainable cars.

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Basically, noise is the unwanted sound that propagates through a medium with a particular magnitude and frequency. Meanwhile, the vibration refers to the displacement of the body at specific reference and time. Although there are various noises in the vehicle cabin, they are classified based on their transmission into two categories; airborne and structure borne noises. The airborne noises refer to the noises produced due the interaction of a moving vehicle with the air volume. Meanwhile, the structure borne noise is caused by the structures of vehicles such as system transmission, suspension, exhaust and body structural and interior acoustic resonances.

In the context of acoustics, the sound quality refers to the noise, vibration and harshness of sounds in the interior vehicle cabin. While the noise and vibration can be measured, the harshness refers to the perceived vibration that can be adequately assessed by subjective feelings of the driver and passenger. The concept of sound quality refers to the objectives measures used for predicting the human's subjective preferences toward noise (Lyon, 2000). It is influenced by physical sound, psychoacoustics (human perceptions) and psychological (evaluation of the perceived sounds) (Genuit, 2004).

Apart from this, human ear perceives sounds in a complex process related to the physics of human hearing whereby the perceived sound is not exactly similar to the emitted one (Xing, Wang, Shi, Guo, & Chen, 2016). Furthermore, the perceptions of customers toward vehicle's sound quality is dependent on their expectations and context. The expectations refer to the cultural demographic and experiences, and the context refers to the situations or environments where the sound is perceived.

In vehicle design, there is no clear definition or an indication to which the phenomena of sound quality is addressed by noise or vibration. In fact, depending on how the phenomena are perceived by the driver or passenger they are considered either as noise or vibration. However, most of the noise vibration phenomena occurs at 100 Hz and 500 Hz which are the frequency range that signifies the airborne and structure-borne noise and vibration. While high frequency vibrations can degrade comfort and sustain local effects, low frequency vibrations have considerable impact on health such as the vibrations in the range of 4-6 Hz causes cyclic motions and resonance to the body, and vibrations up to 12 Hz impact all human organs (Hostens, Papaioannou, Spaepen, & Ramon, 2003).

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As a matter of fact, repetitive exposure to noise and vibrations causes serious health issues including stress, muscles fatigue, mental health issues, sleep disorder, and deafness at higher annoyance levels. Indeed, the transmission of vibration to a driver or passenger has significant influences on their performance, comfort and health (Howart & Griffin, 1990; Paddan & Griffin, 2002). In some cases, long-term exposure to a vibrating components such as seats, wheels, and flooring systems can lead to Whole Body Vibration (WBV). The severity of noise vibration depends on the magnitude, frequency, duration, direction, body size, vibration motion, body posture, composition and body tension to which the exposure occurs (Genuit, 2004).

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Over the years, assessing the sound quality in the interior vehicle cabin has received significant consideration from automotive researches and engineers. As a result, various studies have been conducted to evaluate, improve and predict the sound quality in vehicles (Nor, Fouladi, Nahvi, & Ariffin, 2008; Panza, 2015; Tan, Wang, & Li, 2011; X. Wang, 2010; Y.S. Wang, Shen, & Xing, 2014; Xiao, Wang, Shi, & Guo, 2013). The most common approach to predict sound quality is the Jury subjective test which enables ranking the noise in a qualitative scale. However, the Jury assessment is costly, time consuming and produces irreproducible results as it relies on the subjective impressions made by the human subjects which obviously varies between individuals and are difficult to be represented in quantitative scale (Faris, BenLahcene, & Hasbullah, 2012). In addition, engineering designs requires exact answers and procedures to predict noise, and hence the qualitative impressions made by subjects alone are not enough to assess and improve vehicles' noise vibration characteristics.

Consequently, the psychoacoustic parameters including loudness, sharpness, roughness and fluctuation strength have been developed to illustrates the dimensions of sounds in terms of subjective descriptors without the necessity to conduct the Jury test (Fastl & Zwicker, 2006). These objective measures have been utilized by various researchers in an attempt to evaluate the vehicle interior noise (Leite, Paul, & Gerges, 2009; Nopiah, Junoh, & Ariffin, 2013c; Y.S. Wang et al., 2014). Moreover, though these metrics, multiple algorithms and approaches have been developed and extended, yet the sound quality in vehicles remains a challenging task in automotive industries.

This study proposes a novel formulation of Noise Isolation Index to evaluate acoustical comfort in vehicles. Unlike the previous studies which focused on only one or two types of the interior noises, this study aims to consider both interior and exterior sounds to evaluate the overall acoustics level in the interior vehicle cabin. The proposed index is based on categorizing the sounds into interior and exterior based on the experimental design and data collection procedure. The NII index is developed and validated for three local compact cars namely, Axia, Myvi and Viva. Apart from this, this study also conducted clustering process to cluster the noise and vibration exposures in order to determine and compare the level of comfort in the test cars. Besides that, this study also developed Genetic Algorithm model to optimize the noise and vibration in the interior vehicle cabin of the three test cars. In addition, statistical models have been carried out to validate and compare the results of comfort in each car. The study also aims to determine the impact of road surfaces, engine transmission and type of vehicle on the overall comfort produced in the interior cabin.

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1.2 Research Problem Statement

Due to the ever increasing demands for suppressing and reducing undesirable noise and vibrations in the vehicle interior cabin, various testing procedures and tools have been developed to optimize vehicle characteristics, predict sound quality and assess the noise and vibration (Duan et al., 2015; Hanouf et al., 2015; Huang et al., 2016; Kužnar, Možina, Giordanino, & Bratko, 2012; Nor et al., 2008; Stylidis et al., 2015; Y. S. Wang, 2009; Wanger & Kallus, 2015; Xiao et al., 2013; Zhang et al., 2015).

In addition, under the conditions that the human perceptions toward experienced sounds and vibrations are complex and hard to be estimated, various methods and models have been proposed over the years such as the psychoacoustic metrics (Leite et al., 2009; Yan Song Wang, Shen, Guo, Tang, & Hamade, 2013), statistical models mainly correlation and regression (Kim, Lee, & Na, 2010), the neural network (Yoon et al., 2012), support vector machine (Shen, Zuo, Li, & Zhang, 2010; Xiao et al., 2013), the particle swarm optimization neural networks (PSO-NNs) (Ding, Li, Su, Yu, & Jin, 2013), back propagation neural networks, BPNN (Y.S. Wang et al., 2014), and more recently the genetic algorithm optimal support vector machines (GA-SVMs) (Huang et al., 2016).

However, the fact remains that there is not a universal index which enables assessing the noise and vibration in the interior vehilce cabin. The specific limitation of the proposed neural networks is that, they are shallow and have no hidden layer which means the solutions produced are restricted and the methods proposed for assessing the noise vibration in the interior cabin should be investigated further (Huang, Li, Yang, Lim,

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& Ding, 2017). Unlike the previous studies which focused on only one or two types of noises, it is necessary to develop a powerful and holistic approach that can specify all sounds in vehicles and include all human feelings toward the perceived sounds (Huang, Li, Huang, Lim, & Ding, 2016).

Despite the success of various methods, the more effective prediction of vehicle interior sound quality remains problematic and challenging. Based on the above studies and considerations, the problem statements are:

i. The interior noise vibration is a multi-dimensional phenomena composed of various sources, different and integrated transmission paths, speed changing and ergonomics. Thus, identifying and controlling such phenomena is still a major challenge to vehicle designers and automotive engineers.

ii. The necessity to develop and validate holistic methods and sound quality prediction techniques to assess the interior and exterior sounds and to determine the acoustics comfort in vehicles' cabin thus enabling automotive industries to remain successful and competitive.

iii. There is no specific device that could test the level of comfort in the interior vehicle cabin commercially. This is because understanding the dimensions of sound quality have not been achieved as it requires developing a universal taxonomy of the perceived quality. Thus the methods proposed for assessing the interior noise and vibration should be investigated further.

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1.3 Research Objectives

The specific objectives of this study are:

i. To develop acoustical comfort index called Noise Isolation Index (NII) to evaluate the acoustical comfort in the vehicle cabin by considering the psychoacoustics measures of the exterior and interior sounds.

ii. To cluster noise and vibration using K-mean clustering algorithm in order to compare the interior comfort level of Axia, Myvi and Viva on stationary (idle), non-stationary (highway, pavement and urban) driving conditions.

iii. To develop Genetic Algorithm (GA) model to obtain the comfort level in the interior vehicle cabin. GA aims to search for the promising loudness and vibration values which produce minimum noise in the interior vehicle cabin.

1.4 Research Scope

The particular scope of this study is to assess the acoustical comfort in the interior vehicle cabin of the three local compact cars namely Axia, Myvi and Viva on both stationary (idle) and non-stationary (highway, pavement and urban) conditions. However, the scope is not limited to the following sentences:

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i. To revise the previous works on sound and vibration to identify the factors which influence the discomfort in the interior vehicle cabin. Identifying the factors that influence the level of discomfort in vehicles is critical step toward developing the necessary measures to reduce and control these sources and or tuning them to be pleasant.

ii. To determine the impact of different road surfaces on influencing the acoustical comfort levels in the interior vehicle cabin. The scope of this is limited to the tested roads locations (highway, urban and pavement) which are located at (Changlun-Arau highway, Pauh Putra, near DK1 pavement road and Kampong Arau area urban). It is also limited to the tires used during measurements which are 175/65R14, 175/65R14 and 165/55R14 for Axia, Myvi and Viva respectively.

iii. The scope also limited to the points of measurements of both sounds and vibrations which are front left (interior and exterior sides), right (interior and exterior) and front dashboard for sounds, front and rear floors, front and back dashboards for vibrations.

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1.5 Research Significance

The primary purpose of this study is to optimize the vehicle interior noise and vibration to improve the interior comfort level. Overall, the significances of this study are: