ANALYSIS OF DRUM BRAKE SQUEAL

MUHAMMAD NAJIB BIN ABDUL HAMID

UNIVERSITI SAINS MALAYSIA

2015

ANALYSIS OF DRUM BRAKE SQUEAL

by

MUHAMMAD NAJIB BIN ABDUL HAMID

Thesis submitted in fulfilment of the requirements

for the degree of

Doctor of Philosophy

June 2015

ACKNOWLEDGEMENT

Praise and thanks are due to Almighty Allah, the Most Gracious the Most Merciful.

I would like to express my truly gratitude and highest appreciation to my supervisor Prof. Dr Zaidi Mohd Ripin for his precious guidance, support, training, advice and encouragement throughout my PhD study. His encouragement, motivation and personal guidance have provided a good basis for the completing this thesis.

I would like to express my gratefulness to my beloved family for their support especially to my parents Abdul Hamid and Wan Hasanah, my beloved wife Nor Shaadah and kids; Aiman and Amni who have done most excellent in providing me moral support. I would also acknowledge my entire friends at School of Mechanical Engineering especially Mr. Tan Yeow Chong, Mr. Ahmad Zhafran, Mr Teoh Choe Yung, Mr Mukridz, Mr Izudin, Mr Kamal and Mr. Tarmizi for their great and favourable support. Special thanks to the Mr. Wan Mohd Amri Wan Mamat Ali, Mr Baharom Awang, Mr Mohd Syahril Yusof and Mr. Azhar for the technical guidance and useful suggestion. I also would like to thank all the technicians for their valuable support and help.

My special acknowledgement is also dedicated to Universiti Kuala Lumpur and Majlis Amanah Rakyat (MARA) for providing me with the scholarship scheme during my study. A truly thankfulness are dedicated to all who involve in this project directly and indirectly. Thank you very much.

MUHAMMAD NAJIB ABDUL HAMID
June 2015

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

Symbol	Description	Unit
F	Force	N
F_f	Friction force	N
F_N	Normal force	N
T	Torque	N.m
μ	Friction coefficient	
μ_k	Kinetic friction coefficient	
v_s	Sliding speed	
θ	angle	degree
k_c	Contact stiffness	N/m
C_r	Torsional damping coefficient	$kg.m^2.s^{-1}.rad^{-1}$
C_{r1}	Torsional damping coefficient of mode 1	$kg.m^2.s^{-1}.rad^{-1}$
C_{r2}	Torsional damping coefficient of mode 2	$kg.m^2.s^{-1}.rad^{-1}$
d	Location of centre of contact pressure from elastic axis	m
J	Moment of inertia	$kg.m^2$
J_1	Moment of inertia of mode 1	$kg.m^2$
J_2	Moment of inertia of mode 2	$kg.m^2$
k	stiffness	N/m
K_{r1}	Torsional stiffness 1	$N.m.rad^{-1}$
K_{r2}	Torsional stiffness 2	$N.m.rad^{-1}$
α	Angle between pressing force and normal force of contact	degree
λ	Complex eigenvalue	
$Re(\lambda)$	Real part of complex eigenvalue	
$[B]$	Coriolis matrix	
$[M]$	Mass matrix	

$[K]$	Stiffness matrix	
$[C]$	Damping matrix	
$[K_f]$	Friction interface stiffness matrix	
r_1	Position vector of first node	m
r_2	Position vector of second node	m
$\{A\}$	Acceleration vector	m/s^2
$\{V\}$	Velocity vector	m/s
$\{\Omega\}$	Rotation vector	Hz
T^i	Kinetic energy at node *i*	J
m_i	Mass of node *i*	kg
α	Mass proportional damping coefficient	
β	Stiffness proportional damping coefficient	
$\{X\}$	Displacement vector	m
$\{F\}$	Force vector	N
s	Complex variable in Laplace domain	
ω_N	Natural frequency	Hz
$\{\psi\}$	Modal eigenvector	

ANALISIS BUNYI KIUT BREK GELENDONG

ABSTRAK

Bentuk lenturan semasa operasi digunakan untuk menentukan mod bentuk getaran bagi kasut brek semasa kejadian bunyi kiut brek gelendong. Pengukuran bentuk lenturan semasa operasi bagi kasut brek adalah didapati dalam mod pulasan dan menyamai mod bentuk yang diperolehi melalui eksperimen modal bagi kasut brek dalam keadaan bersentuhan dengan gelendong brek. Model matematik bagi darjah kedua kebebasan dihasilkan dengan menggunakan maklumat daripada eksperimen modal dan juga frekuensi bunyi kiut iaitu 1850 Hz. Dalam kajian ini, bentuk lenturan semasa operasi digunakan dalam melaksanakan ubahsuai struktur dinamik kepada kasut brek bagi meningkatkan kestabilan sistem brek. Model parameter tergumpal bagi kasut brek ini digunakan untuk menilai kesan ubahsuai struktur dinamik dengan kaedah analisis fana. Model matematik tersebut menghasilkan keputusan yang hampir sama dengan eksperimen dan ini membolehkan para jurutera menilai parameter yang penting dalam menghasilkan brek gelendong yang bebas dari bunyi kiut. Seterusnya, bunyi kiut grek gelendong ini dianalisa pula menggunakan kaedah unsur terhingga. Kajian kedua meliputi kestabilan dinamik bagi brek gelendong yang terdiri daripada satu gelendong yang berputar dan dua kasut brek yang static yang mana kesan putaran diambil kira dalm analisis nilai eigen kompleks. Pengaruh kelajuan putaran gelendong diwakili oleh kesan Coriolis and daya empar. Hasil kajian menunjukkan satu mod tidak stabil pada 1658 Hz dan nilai ini hampir dengan frekuensi yang diukur. Apabila kelajuan ditingkatkan, bahagian positif pada nilai eigen kompleks menurun dan menjadi negatif apabila kelajuan melebihi 600 putaran seminit.

ANALYSIS OF DRUM BRAKE SQUEAL

ABSTRACT

The operational deflection shapes were used to identify the mode of vibration for the brake shoes in drum brake squeal. The measurement of the operational deflection shapes of the brake shoes during drum brake squeal, which was in the torsional mode, was similar to that of the modes obtained from the experimental modal analysis of the brake shoe under the in-contact static condition. A two-degree-of-freedom model was developed on the basis of the experimental modal analysis data within the limited bandwidth of the squeal frequency of 1850 Hz. In this work, the operational deflection shape was used for determination of a structural dynamic modification to be carried out on the brake shoes in order to maximize the damping of the torsional mode as a way to improve the stability of the system. The lumped parameter model was then used to assess the effect of the structural dynamic modification on the squeal based on the transient analysis, which showed a similar trend and can assist brake designers in evaluating the critical parameter to obtain a squeal-free drum brake design. The drum brake squeal was further analysed using finite element method. The second part of this study was the dynamic instability of a drum brake system, which consists of a rotating drum and two immobile brake shoes which took into consideration the rotation effect on the complex eigenvalue. The Coriolis force and the centrifugal load represented the effect of the rotation of the drum. The results indicated an unstable mode at 1658 Hz, which is equivalent to the measured frequency of the drum brake squeal. As the speed was increased, the positive real part of the complex eigenvalue Re(λ) decreased and became negative at speeds beyond 600 rpm.

CHAPTER ONE
INTRODUCTION

1.1 Background

The brake, which is designed to absorb the kinetic energy in the process of slowing down or stopping, is one of the most important elements in the automotive industry. The earliest types of brakes used on motor vehicles were drum brakes. These days, over 100 years after it was first used, drum brakes are still used on the rear wheels of most vehicles. The drum brake is generally used as the rear brake, particularly for small cars and motorcycles. Drum brakes are essential for buses and trucks, especially on the drive axles and trailer tandems, because of the low manufacturing cost and the ease of integrating the parking brakes. The leading-trailing shoe design is widely used as the rear brakes on passenger cars and lightweight pickup trucks, in fact, most front-wheel drive vehicles use rear leading-trailing shoe brakes, the configuration of which provides a design that has low sensitivity to lining friction changes and a stable torque production (Limpert, 1999).

Vehicle comfort has become an essential factor in signifying the quality of a passenger car. In fact, vehicle quietness and passenger comfort issues are key concerns. The brake system is one of the vehicle components that usually produce unnecessary vibrations and noise. Brake noise is a problem that is related to comfort and enhancement, rather than performance. Moreover, this problem could possibly lead to high warranty costs and contribute to common brake fault claims. The warranty costs for brake Noise, Vibration and Harshness (NVH) in North America has reached one billion dollars a year (Akay, 2002).

Generally, brake vibrations and noise can be split into two perceptible categories based on the frequency range. The first is brake judder which can be felt rather than heard and typically occurs at frequencies below 100 Hz. The second is noise which is a result of self-excited oscillation or dynamic instability and occurs at frequencies above 1 kHz and is usually known as a squeal or squeak. A review by Kinkaid et al. (2003) listed all brake noise and vibration phenomenon described by its own terminology such as squeal, creep-groan, moan, chatter, judder, hum and squeak.

Studies on brake noise and vibration endeavoured to identify techniques for eliminating and reducing the noise and vibration and then eventually focused on its generation mechanisms. Eliminating or reducing the noise and vibration of a vehicle structure and system appears to provide a leading edge in the market for vehicle manufacturers given that vehicle comfort has become such an important factor to indicate the quality of a passenger car. The refinement in brake vibration and noise is inevitable in light of the progress made in improvement towards other aspects of vehicle design refinement against vehicle vibration and noise. This is evidenced from the literature where the awareness on the brake vibration and noise issues begun as early as 1930's (Bakar, 2005). From then on, the problem of the noise and vibration in brakes has been studied using experimental, analytical, and computational methods. However, up to now, there has been no method to totally suppress brake noise and vibration in general, and squeal in particular. Furthermore, a complete understanding of the problem has not yet been achieved and these could be due to the complexity of the mechanisms itself and competitive nature of automotive industry which limits the amount of cooperative research to be published in the open literature (Papinniemi et al., 2002).

1.2 Problem statement

The drum brake squeal is a friction induced vibration, mainly in the frequency range of 1 kHz to 16 kHz, and produced by the unstable vibrations of the brake system (Papinniemi et al., 2002, Kinkaid et al., 2003). The noise of a brake squeal directly affects the public, making it a major concern. There are several major reasons listed by The American Public Transport Association for the drum brake squeal which are generally linked with the condition of the brake lining and the irregular contact of the drum and the shoe due to the bell mouthing of the drum (American Public Transportation Association, 2010). A maximum noise level of 89 dBA was measured on the New York Transit system at several bus stops, which is deemed very high (Gershon et al., 2006). Furthermore, complaints can still be found in public forums on the web relating to the noise caused by drum brakes, and these issues are being seriously attended to by car manufacturers.

Generally, the drum brake squeal shares the same friction-excited vibration mechanism as the disc brake squeal but, the availability of experimental data to support the various models is limited. There is a need to acquire experimental results, including friction coefficient and Operational Deflection Shape (ODS) of the brake shoe during a squeal, to further analyse the drum brake squeal. Most of the mathematical model of drum brake squeal was not experimentally verified with squeal measurement. While the minimal model of brake squeal is verified with experiment, it could be used to analyse drum brake squeal in order to reduce or eliminate the squeal. On the aspect of modelling, when performing an eigenvalue analysis, researches concerning drum brakes did not take into consideration the rotational effect specifically in the Finite Element Method (FEM) model. The latest study by da Silva et al. (2013) disregarded the rotational effects as it assumed that the rotational speed was not high enough to affect the dynamic performance of the assembly. Nevertheless, there is no computation available to indicate the particular speed at which the Coriolis force becomes significant. Thus far, no findings have been published concerning the rotational effect on the drum brake squeal using the complex eigenvalue method.

1.3 Research objective

The objectives of this research are to:

1. Identify squeal mode for the structural dynamics modification for drum brake squeal attenuation on the brake shoe based on the experimental modal analysis results and operational deflection shapes.
2. Develop minimal model (two degree-of-freedom lumped parameter model) of drum brake squeal using modal parameters based on the in-contact condition and verify with squeal measurement for the brake shoe to identify parameters that can be used to attenuate the drum brake squeal.
3. Investigate the rotational effect in terms of Coriolis force in the stability analysis using complex eigenvalue for the drum brake squeal.

1.4 Research scope

This research is focused on the analysing drum brake squeal in order to suppress or reduce squeal level. Squeal mode is identified using operational deflection shape analysis (ODS) and mode shapes of natural frequencies obtained from experimental modal analysis. The squeal mechanism for this analysis is mode coupling mechanism or sometimes called binary flutter mechanism (Ghazaly et al., 2014). The two modes that will merge or couple is identified using experimental modal analysis for brake shoe in-contact condition with the drum. All this information from EMA & ODS is used to develop minimal model (two-degree-of-freedom lumped parameter model) based on the squeal mode obtained. Stability analysis of drum brake squeal is performed using complex eigenvalue analysis by utilising ABAQUS FEA software and Coriolis force is added into FE model when analysing rotational effect on the stability analysis.

1.5 Contribution

The mode of vibration for the brake shoe in the drum brake squeal is identified using the operational deflection shape (ODS). The measured ODS of the brake shoe during the squeal exhibited a torsional mode and was akin to one of the modes acquired from the experimental modal analysis of the brake shoe under the in-contact static condition. Based on these, a two degree-of-freedom model was developed, showing good correlation and could be a useful tool in analysing brake squeal using a minimal model of brake shoe. With this, design stability can be attained by Structural Dynamics Modification (SDM) where increasing proportional damping by adding webs (therefore adding mass and increasing stiffness) to the brake shoe flange lessens the vibration level. The Rayleigh damping model can be written as $[C] = \alpha[M] + \beta[K]$ where M and K are the mass and stiffness matrices respectively. From this equation the damping is affected by the change in stiffness by the coefficient β. SDM was used by adding webs (stiffeners) to the brake shoes that will increase stiffness and damping (proportional damping) which are to improve stability This is important as it is the first time the SDM technique together with ODS of the drum brake squeal has been applied to effectively reduce the drum brake squeal amplitude.

By including the Coriolis force effect, which is speed dependant, the rotational speed effect is included in the overall equation of motion. The complex eigenvalue analysis of the drum brake system with this effect illustrates that the eigenvalues are speed dependant. The results pointed out an unstable mode which is equivalent to the measured frequency of the drum brake squeal. With the increase of speed, the positive real part of the complex eigenvalue Re(λ) decreased and became negative, signifying a stable configuration at speeds above 600 rpm. This explains why the squeal does not occur at high rotational speed although friction coefficient is high i.e. the Coriolis force due to the rotation of the drum has a stabilizing effect on the drum brake system.

1.6 Thesis outline

This thesis is presented in six chapters i.e. introduction, literature review, methodology, theory, results and discussion and lastly, conclusion.

Chapter One, consisting of the introduction and background of the analysis, includes problem statement, research objectives and contribution. Chapter Two puts forward the literature review. The previous analysis regarding to the brake system, and brake squeals in particular, are reviewed and discussed. Chapter Three describes the methodology used in this analysis, which are experimental, mathematical model and finite element modelling. Meanwhile Chapter Four expounds the theory of the mathematical model development, structural dynamics modification, and the Coriolis Effect on the stability analysis using complex eigenvalue. Chapter Five presents the results as well as the discussions. The conclusion and recommendation of the present analysis are given in Chapter Six.

CHAPTER TWO
LITERATURE REVIEW

2.1 Overview

This section discusses some basic knowledge and major findings in a review of the literature regarding drum brake squeal. The review comprises topics pertaining to the main scope of the brake squeal theory and mechanism, the experimental and analytical study of brake squeal, and a discussion of the reviewed papers.

The objective of this literature review is to provide a basic understanding of the problem of brake squeal in terms of its mechanism, previous and current analytical methods, and findings on brake squeal. It also highlights some current issues that have not been considered by brake researchers, especially with regard to the modelling and simulation of drum brake squeal through the finite element method.

2.2 Introduction

Automotive friction brakes are made up of the drum and disc brakes. The drum brakes can be further divided into simplex, duplex and duo servo drum brakes (Halderman and Mitchell, 2004). Drum brakes have brake shoes that push the brake lining against the drum in a radial direction. Drum brakes are cheap and not very complicated, and they are more effective because of the self-amplification system, whereby the drum brake is designed to push the brake lining firmly against the drum by means of a self-energizing action. One disadvantage of the drum brake is that they are more susceptible to brake fade because of problems with heat transfer and cooling. Meanwhile, disc brakes are not as sensitive to brake fade but they are more costly and are not as effective at braking as drum brakes (Mahmoud, 2005). The