MODELLING DAMPING ELEMENT TO REDUCE DISC BRAKE SQUEAL

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A thesis submitted in fulfillment of the
requirements for the award of the degree of
Master of Engineering (Mechanical)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

FEBRUARY 2013

Dedicate to my beloved mother, father, wife and brothers.

ACKNOWLEDGEMENT

Alhamdulillah, all praise is due to Allah S.W.T, the Most Beneficent and the Most Merciful, who has taught me what I knew not.

I would like to express my deepest appreciation to my project supervisor, Dr. Abd. Rahim Abu Bakar for all the advices, guidance and motivation given throughout this thesis. I also like to give my sincere thanks for giving me the opportunity to do this research. This research work has given me valuable experience especially in learning modeling and simulation. Special thanks also to my co-supervisor Dr. Mohd. Zarhamdy Md. Zain for his inspiration, teaching and advices.

I would like to further extend my gratitude to all lecturers, researchers, my friends in FKM and FKE, all suppliers and technicians who has assisted me directly and indirectly throughout the progress in completion of my project. I will not forget all opinions and supports given

Last but not least, I want to whole heartedly give my appreciations to my beloved mother, father, wife and brothers for giving me the unlimited supports and motivation when I faced the difficulties in carrying out this project.

Thank You.

ABSTRACT

A disc or drum brake system is very often generating undesirable and annoying squeal noise that can disturb both driver and passengers. In order to prevent or reduce brake squeal noise, structural modifications of brake components, damping layers and active squeal control methods are commonly proposed and evaluated by car manufacturers using analytical, numerical and experimental approach. Thus, this thesis attempts to investigate the effectiveness of damping layers such as pad insulator and clip to reduce disc brake squeal noise. In doing so, existing two (pad model) and four (pad-disc model) degrees-of-freedom (DOF) brake models without damping layers are adopted. The mass, stiffness and damping values of these brake models are obtained from the experiments. These two brake models are then validated against a real brake assembly test data and good correlation on the natural and squeal frequency is achieved. Upon obtaining validated brake models, damping layers i.e. the clip and insulator are modelled based on its mass, stiffness and damping. The layers later are embedded into the validated pad and pad-disc models. The parameter properties (stiffness and damping) of these damping layers are measured from modal testing. Complex eigenvalue (CE) and dynamic transient (DT) analyses are performed using MATLAB software package to predict squeal occurrences. The squeal trigger mechanism used in this work is based on mode coupling effect. The brake models with damping layers are simulated at a certain brake parameter range such as friction coefficient, pad-disc contact stiffness and pad wear. From the analysis, it is found that both CE and DT predict squeal frequency close to the measured data with difference less than 4%. It is also found that the pad-disc model is successfully predicting squeal or non-squeal occurrences close to the squeal test results for both with clip and clip-insulator models. However, the pad model is seen not capable to completely replicate the squeal test results particularly with the clip model. This shows that the pad-disc model should be used to predict squeal occurrences. From the parametric studies, it is shown that squeal noise can be

completely eliminated for a wide range of friction coefficient, pad-disc contact stiffness and pad wear. This can be suggested that the clip-insulator combination is indeed effective in preventing squeal noise.

ABSTRAK

Sistem brek cakera atau gelendong seringkali menghasilkan bunyi decitan yang tidak diingini dan akan mengganggu para pemandu dan penumpang. Dalam usaha untuk mencegah atau mengurangkan bunyi decitan brek, pengubahsuaian struktur komponen brek, lapisan redaman dan kaedah kawalan bunyi decitan aktif biasanya dicadang dan dinilai oleh pengeluar kereta secara kaedah analitik, berangka dan eksperimen. Oleh itu, tesis ini cuba mengkaji keberkesanan lapisan redaman seperti klip dan penebat dalam usaha untuk mengurangkan bunyi decitan daripada sistem brek cakera. Dalam menjalankan kajian ini, model sedia ada iaitu dua-(model pad) dan empat-(model pad-cakera) darjah kebebasan (DOF) digunakan. Nilai jisim, kekakuan dan redaman untuk kedua-dua model brek ini diperolehi melalui eksperimen. Kedua-dua model ini disahkan melalui data ujian brek sebenar di mana pertalian yang baik untuk frekuensi nyata dan frekuenci bunyi decitan diperolehi. Setelah mendapatkan kesahihan model brek, lapisan redaman iaitu klip dan penebat dimodelkan mengikut nilai jisim, kekakuan dan peredam. Lapisan ini kemudiannya dimasukkan ke dalam model pad dan pad-cakera. Nilai parameter (kekakuan dan redaman) lapisan redaman diukur dari data ujian modal. Nilai Eigen (CE) dan analisis dinamik fana (DT) dilakukan menggunakan pakej perisian MATLAB untuk meramalkan berlakunya bunyi decitan. Mekanisma bunyi decitan terhasil dalam kerja ini hanya mengambil kira kesan gandingan mod. Model brek dengan lapisan redaman disimulasikan pada pelbagai parameter brek tertentu seperti pekali geseran, kekakuan antara pad cakera dan kehausan pad. Daripada analisis, didapati bahawa CE dan DT meramal frekuensi decitan hampir sama dengan frekuensi melalui eksperimen dengan perbezaan kurang daripada 4%. Didapati juga bahawa model pad-cakera berjaya meramal bunyi decitan dan keadaaan tanpa bunyi decitan hampir sama dengan keputusan bunyi decitan eksperimen untuk model klip dan klip-penebat. Namun, model pad dilihat tidak berupaya untuk menyamai keputusan

eksperimen terutama pada model klip. Ini menunjukkan bahawa model pad-cakera perlu digunakan untuk meramal berlakunya bunyi decitan. Daripada kajian parameter, ia menunjukkan bahawa bunyi decitan boleh dihindari bagi julat pekali geseran, kekakuan sentuhan pad-cakera dan kehausan pad yang besar. Ini merumuskan bahawa gabungan klip dan penebat sangat berkesan untuk menghalang bunyi decitan.

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LIST OF ABBREVIATIONS

FE	-	Finite Element
FIV	-	Friction Induce Vibration
CEA	-	Complex Eigenvalue Analysis
DTA	-	Data Transient Analysis
NVH	-	Noise, Vibration and Harshness
DOF	-	Degree of Freedoms
EMA	-	Experimental Modal Analysis
DPHI	-	Double-Pulsed Laser Holography Interferometry
ESPI	-	Electronic Speckle Pattern Interferometry
FEM	-	Finite Element Method
DOE	-	Design of Experiments
ACSL	-	Advanced Continuous Simulation Language
DPT	-	Derjaguin-Push-Tolstoi
AFC	-	Active Force Control

LIST OF SYMBOLS

Hz	-	Frequency unit
dB	-	Decibel
mu-v	-	Negative slope
m	-	Mass
c	-	Damper
k	-	Spring
x	-	Displacement in-plane
y	-	Displacement out-plane
μ	-	Friction coefficient
v	-	velocity
g	-	gravity
θ	-	angle
F_f	-	Fricion force
N	-	Normal force
R	-	Reaction force
kg	-	Kilogram
N/m	-	Newton per meter
Ns/m	-	Newton second per meter
N	-	Newton
m	-	meter
m/s	-	meter per second

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

Brake system is an important safety system in the passenger car to slow down or for complete stop and to hold to hold the vehicle stationary while parking. During braking process the brake pads come into contact with a rotating disc which generated friction which slows down the car and finally make it stop. During braking, this friction force may also induce dynamic instability to the system and leads to unwanted vibration and unpleasant noise. This undesired brake noise may cause discomfort to drivers and passengers. There are a number of terminologies to describe this noise and vibration phenomena such as squeal, groan, chatter, judder, moan and hum [1]. Among of these categories, squeal is the most annoying and disturbing. According to Lang and Smales [2] brake squeal is usually generated at frequency above 1 kHz and Eriksson [3] stated that a sound pressure level for the squeal is set at 78 dBA and above. Hence, brake squeal is a major concern not only to the customers due to the uncomfortable and irritating sound but also to the car makers, brake and friction suppliers where every year they have to bear a high cost payment for warranty claims by customers [4-6].

1.2 Problem Statement

Brake squeal is an unpleasant sound that might reduce both driver and passenger comfort feeling. However, until now brake squeal issue remains completely unresolved despite large efforts have been done to understand, to predict and to eliminate squeal using various methods from a lower order disc brake model (theoretical) to a high complexity model (finite element) and the use of sophisticated squeal experimental work.

Amongst those mentioned methods, theoretical method is cheap and fairly fast in providing solution [7]. However in practice the theoretical model is said to be inadequate to resemble a real disc brake assembly. Nevertheless, theoretical method can at least be used in the early brake design stage in order to predict squeal occurrence and to provide countermeasure against squeal. Unlike theoretical method, finite element (FE) method can predict squeal with a better accuracy. An FE model can be developed accurately to replicate a real brake assembly. However, the main disadvantage of this technique is the requirement of computer intense and it demands a long simulation time especially when performed on the high complexity FE model [8]. Although experimental work can provide result based on a real condition of disc brake system, the hardware and software development are expensive and required a significant time to complete the designing process. In addition, discoveries made on a particular type of brake are not always transferable to other types of brake and quite often product developments are based on trial-and-error basis [9].

It is well accepted that brake squeal is a result of a friction induced vibration (FIV) [1]. To date, numerous FIV models [10-27] have been proposed and some of them were said to represent brake squeal model [12-27]. These models were typically incorporated with acceptable squeal trigger mechanisms such as mode coupling [11-15] and negative gradient of friction coefficient over sliding speed (*mu-v*) [16-21]. However, Chen and Zhou [28] suggested that negative *mu-v* behavior is not a necessary condition for squealing brake whilst Wagner *et al.* [29] believed that mode coupling is more realistic cause of brake squeal.

In predicting squeal propensity there are in general, two major techniques available: complex eigenvalue analysis in the frequency domain and dynamic transient analysis in time domain. Both analyses have their pros and cons. The complex eigenvalue analysis can reveal which system modes of vibration are unstable but a shortcoming of this technique is that they do not allow time-dependant material properties and could not take into account full effect of nonlinearity away from steady sliding [8]. Meanwhile, divergence of a transient solution indicates that instability is present in the system and this technique could overcome the shortcomings in complex eigenvalue analysis with the drawback long computing time and slow turnaround time for design iterations.

There are a number of techniques have been introduced in order to reduce squeal and they are damping layer [30-34] structural modification, structural modifications [7, 35-41] and active noise control [43-45]. These three techniques are commonly incorporated in the finite element model [46-56] and experimental works [57-66] but very rare in the lower order model except for active noise control [43-45]. It is seen that damping layer is mostly preferred by car makers and brake suppliers due to its capability to suppress squeal and cost effective compared to the other techniques. However most of the previous researches for damping layer are on the finite element and experimental approach. The existing analytical models almost did not consider the damping element rather previous researchers were only used a range of parameters for damping layer [30-34] to predict stability of the brake system.

Thus, the present study aims to investigate squeal using lower order of disc brake models where Butlin and Woodhouse [67] suggested that it is sufficient for the lower order brake model, e.g. three-degree-of-freedom brake model to give a reasonable approximation to the global prediction. The selected models are then incorporated with mode coupling effect. In order to prevent squeal, damping layers such as insulator and clip are considered and modeled. Complex eigenvalue and dynamic transient analysis are performed to predict squeal occurrence.

1.3 Objective of the Study

The main objectives of this research are to predict brake squeal by using a lower degree of freedom brake model that initially considers pad/disc element, to include damping layer model for pad shim and clip ,and finally to assess the effectiveness of these damping layers against squeal.

1.4 Scope of Study

The scope of study is as follows:

i. Existing two (pad only) and four (pad and disc) degrees of freedom models of a disc brake system are used. All parameter values in the models are obtained from the experiments. Validation of these models is made against test data at assembly level. Complex eigenvalue and dynamic transient analysis are performed to predict squeal between 4 to 5 kHz using MATLAB software package.

ii. Insulator and clip are explicitly modelled as damping layers in order to reduce squeal noise. Their damping and stiffness values are estimated from modal testing.

iii. Mode coupling is the only mechanism considered to contribute for squealing brake.

iv. Verifications of squeal and non-squeal noise are partly made against test data.

1.5 Significance of study

It is essential that brake squeal issue addressed in the early design stage using a proper way, quick turnaround with reasonable outcomes. This can be achieved using theoretical method where to date numerous lower order of brake models are available and some of them can predict brake squeal reasonably well against test data. Furthermore, prevention approaches can also be modelled and incorporated into the lower order of brake model.

Regarding to Dessouki *et al.* [45] disc brake squeal can be identified with three different families:

i. Caliper Bracket induced squeal (2 - 6.5 kHz).
ii. Pad-induced, also defined as axial, or out-of plane squeal (4-11 kHz).
iii. Rotor induced, also defined as tangential, in-plane and longitudinal (7-16 kHz)

Therefore, an existing two [11] and four [45] degrees-of-freedom brake model are selected and analysed. These two models are named as pad model and pad-disc model. Both models consider a translational axis with coupling criteria for out-planes and in plane axis. The model parameters are determined using experimental modal analysis (EMA) to ensure its validity against actually disc brake and squeal test data. Then, insulator and clip models are proposed by introducing mass (m), damper (c) and spring (k) where all the parameter values can be estimated by weight scale (m) and again with modal testing (k and c). The methodology used in this work can be used as design guidelines for brake engineers to predict squeal and later to estimate properties of damping layer that can prevent squeal occurrence in the early design stage.

1.6 Organization of the Thesis

This thesis is organized into six chapters.

Chapter 1: Presents an overview of the research work, objective and scope of the study and methodology of the research.

Chapter 2: Focuses on the literature review that has been carried out related to the main subjects of interest to cover brake squeal and the mechanisms that cause it and the relevant works that have been implemented to suppress it through a number of techniques.

Chapter 3: Concentrates on the methodology of the disc brake squeal modeling using FIV model and provides the overall framework of the complex eigenvalue and dynamic transient analysis.

Chapter 4 Presents squeal prediction results using complex eigenvalue analysis for the baseline model and model with damping layers. Correlation between the predicted and experimental results is sought. Test results for stiffness and damping coefficients of the insulator and clip are also given.

Chapter 5: Summaries the results and provides conclusions of the present work. Recommendations for further work are also presented in this chapter.

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PUBLICATIONS

1. N. Md Yusop, A.R. Abu-Bakar , S. M. H. Dehkordi and M.Z. Md. Zain., “Stability Analysis of A simple Disc Brake System Disc Brake Model Using Eigenvalue Approach” 3rd Regional Conference on Noise, Vibration and Comfort (NVC) 2010,. 28-30th June, 2010, Putrajaya, Malaysia.

2. N. Md Yusop, A.R. Abu Bakar, M.Z. Md. Zain., “Stability Analysis of A Simple Disc Brake Model Using Analytical Approach”. World Engineering Congress 2010, 2nd – 5th August 2010, Kuching, Sarawak, Malaysia.