INVESTIGATION OF BRAKE SQUEAL/SELF INDUCED VIBRATIONS

AMMAR ABDUL MAJEED YOUSIF MOHAMMED

UNIVERSITI SAINS MALAYSIA

JANUARY 2011

INVESTIGATION OF BRAKE SQUEAL/SELF INDUCED VIBRATIONS

by

AMMAR ABDUL MAJEED YOUSIF MOHAMMED

Thesis submitted in fulfillment of the requirements for the degree of Master of Science

JANUARY 2011

ACKNOWLEDGEMENTS

It is my great pleasure to explicitly express my sincere sense of gratitude towards many people involved in this research. Indeed without those great people, this research would not have been possible. Firstly, my deepest thanks go to a number of people who were instrumental in the helping and supporting towards a successful completion of this research. At the outset, I would like to thank my research supervisors and technical staff at USM School of Mechanical Engineering for accepting me and for their feedback and advice during my MSc study. Special thanks go to Doctor Inzarul and Prof. Horizon Walker Gitano for them openness and the stimulating discussions we have had for the last two years which I have learnt immensely from. Thank you Sir.

I would also like to thank the laboratory personnel at USM School of Mechanical Engineering for their kind assistance in carrying out my experimental assignments in a wonderful atmosphere.

Finally, but not the least, I need to thank my father, mother, grandmother and my friends, especially …………………………..for encouraging and supporting me during my stay overseas. Their continuous prayers for me were the driving engines to excel in my studies. Thank you so much for your love and patience. May God bless you!

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF SYMBOLS

A	Amplitude
C	Damping
E	Young’s Modulus
F	Force
F	Frequency
G	Gravity
K	Stiffness
M	Mass
N	Normal force
t	Time
μ	Coefficient of friction
ω	Frequency
Σ	Damping ratio
P	Gradient
A	Density
α	Real part of eigenvalue
j	$\sqrt{-1}$

LIST OF ABBREVIATION

DOF	Degree of freedom
FEM	Finite element method

penyelidikan ke atas bunyi kiut berk/ getaran swaaruhan

ABSTRAK

kebisingan brek hingar persatuan dengan ketidakstabilan dinamik dari sistem dan dikategorikan bergantung pada frekuensi untuk hingar quality (menjerit) dan rendah kebisingan (Mengerang). Pada frekuensi rendah (0-500kHz) model tongkat-slip digunakan untuk menyediakan disc-pad sistem yang diselesaikan dengan menggunakan kaedah ODE45 berangka dengan MATLAB perisian. Model stick-slip adalah kaedah massa bertumpu dengan satu darjat kebebasan. Menyelesaikan model stick-slip membolehkan kita untuk mengetahui gesekan-relatif kurva kelajuan yang digunakan di FE ABAQUS Software untuk mengetahui pengaruh kinetik dan statik geseran pada respon sistem. Keputusan kajian menunjukkan bahawa meningkatkan massa, redaman dan pekali geseran boleh lembap hingar sementara meningkatkan simpulan meningkatkan bunyi sistem. sudut sentuhan antara balok / disc yang juga hyata mempengamhi pada amplitud getaran sehingga sebagai kestabilan yang bertanggung jawab tentang pemisahan permukaan. Lain Analisis yang lain dilakukan dengan frekuensi tinggi (1-12) kHz, plat dengan kelajuan pusingan disc sistem. Software ANSYS telah digunakan untuk menganalisis pengaruh daripada menukar parameter mekanik pada kestabilan sistem. Matrix27 digunakan untuk mewakili kenalan unsur antara plat dan cakera. Keputusan kajian menunjukkan hanya tiga iaitu kerana pengaruh perubahan simpulan kenalan tidak stabil mod sementara dua kerana pengaruh perubahan pekali geseran mode tidakstabil. Kenalan simpulan menghasilkan mod diametral keenam stabil

sementara geseran pekali yang dihasilkan mod diametral ketiga. Ini menunjukkan bahawa kenalan simpulan mempunyai kesan lebih besar kepada kestabilan daripada pekali geseran. Itu unsymmetry dari sistem bertanggung jawab untuk mengurangkan tempoh ketidakstabilan.

INVESTIGATION OF BRAKE SQUEAL/SELF INDUCED VIBRATIONS

ABSTRACT

Brake noise associates with the dynamic instability of the system and is categorized depending on the frequency to high noise (squeal) and low noise (groan). At low frequencies (0-500kHz) a stick-slip model was used to present the disc-pad system which is solved by using a numerical method ODE45 with MATLAB software. The stick-slip model was a lumped mass method with one degree of freedom. Solving stick-slip model enables us to find out the friction-relative velocity curve which is used inside FE ABAQUS Software to find out the effect of kinetic and static friction on response of the system. The results showed that increasing the mass, damping and friction coefficient can damp the noise while increase the stiffness increases the noise of the system. The contact angel between beam/disc has significant effect on vibration amplitude so as the stability which was responsible about the separation of the surfaces. Another analysis was done with high frequencies (1-12) kHz, a plate with rotating disc system. ANSYS Software had been used to analyze the effect of changing the mechanical parameter on the system stability. Matrix27 was used to represent the contact element between the plate and the disc. The result showed only three unstable modes due to the effect of changing the contact stiffness while two unstable modes due to the effect of changing the friction coefficient. The contact stiffness generates the sixth unstable diametral mode while the friction coefficient generated the third diametral mode. It's indicates that the contact stiffness has larger effect

on the stability than the friction coefficient. The unsymmetry of the system was responsible for decreasing the period of instability.

Chapter 1- Introduction

1.1 Brake Background

Brake is a device to stop or to slow the rotating wheel and therefore the moving vehicle by using the friction between the wheel and the pads to slow the motion of the vehicle. The friction created by the contact of two objects together generates a squeal or noise. Brake squeal is a problem which makes the customer uncomfortable and may results in rejection of a certain brands of brake system. After a wide study on brake squeal, it is not yet a completely understood phenomenon. There is no theory to explain or cover this complex problem yet. Brake squeal has been studied by many researchers through experimental, analytical and numerical methods in an attempt to understand and to predict the squeal occurrence. In recent years, the finite element method (FEM) has become the preferred method in brake squeal analysis. The use of FEM is due to deficiency of experimental methods in predicting squeal at early stage in the design process. Moreover, FEM can easily simulate any changes made on the disc brake easier than experimental methods which are time consuming and expensive due to fabrication costs. In addition, that fabrication which is made on a particular type of brake cannot always be used with other type of brake. Brake noise was classified into three types depend on the noise generated in each frequency range, i.e.; brake judder, brake groan and brake squeal. The brake groan and brake squeal are the only focus of this study. Recent researcher show that the coincident of the brake squeal with the natural frequency of the system is the reason to generate the squeal, see e.g. Massi et al. (2007). They associated that modal analysis is an important method to predict the squeal occurrence.

Akay (2002) recently reviewed friction-induced noise, including car disc brake squeal. He quoted from an industrial source an estimate of the warranty cost due to noise, harshness and vibration including disc brake squeal, as US$ 1 billion a year to the automotive industry in North America alone"

1.2 Squeal generation

During the process of stopping the vehicle, the vehicle kinetic energy need to be transformed into some form of energies that can be dissipated in the form of heat and another be transferred into vibration energy. It is generally believed that brake squeal is a self-excited vibration caused by the instability of the brake system. When the brake system has the mechanism to accumulate vibration energy into certain level, squeal will be created. When brake squeal occurs, the rubbing surfaces do not stick and the relative sliding speed is always unidirectional (Lou et al. 2004). In order to reduce or eliminate squeal, it is very important to understand the coupling mechanism so that the key components can be modified accordingly. Complex eigenvalue is widely used as an analytical tool to analyse brake squeal. It is important issue to reduce the squeal during braking in order to improve the quiet and comfortable performance of the vehicle.

1.3 Research objectives

There are four objectives in this thesis.

- Find out the friction relative velocity curve by solving stick-slip model for one degree of freedom and use it inside the FEM software (ABAQUS) to represent the contact between beam-disc systems.
- Study the effect of changing the parameter on system stability by using stick-slip model for one degree of freedom in order to predict the squeal occurrence and observe the effect of increasing the degree of freedom on the stability.
- Study the effect of self-excited vibration in two degree of freedom by using FEM method at low frequencies (0-500)Hz
- Modeling of plate on disc by using ANSYS software to study the effect of certain parameter on the stability at high frequencies (1-12) kHz.

1.4 Thesis outline

This thesis consists of six chapters summarized as follows. Chapter Two comprises literature review on the subject of brake squeal and stick slip motion. Chapter Three covers the methodology of the present work. Chapter four concentrates on the analysis and solution of stick-slip motion and finding the relation between friction coefficient and relative velocity. Chapter five uses FEM to describe thoroughly self-excitation vibration between beam and disc at low velocity speed and model a plate on rotating disc system by using ANSYS software with Matrix27 in order to analyse the effect of different parameters value on the brake stability. Also in this chapter Modal analysis is carried out to visualize the mode that has relation with squeal. The interface is set in a slip condition. The dynamic unstable mode is investigated during squeal where positive eigenvalue is observed.

1.5 Problem Statement

After a wide study about brake noise, the problem is not yet understood and solved. The brake is exhibit two types of noise generated during the brake phenomenon. The difference in the noise is due to the difference in the frequency and the relation between the velocity and friction coefficient. Many researchers studied the brake vibration at low frequency experimentally by using pin on disc. Another study at low frequency is by using stick-slip phenomenon for one degree of freedom. The previous studies use stick and slip conditions to achieve solving the system while in this thesis there is no such condition for the stick and slip formula. At high frequency the researchers modeled a beam on disc to study the effect of the mechanical parameter on the dynamic stability. However, using FEM software opened the door to easy prediction of the effect of this parameter on the stability. The problem of the squeal is not yet solved for that there is a necessity to find a new model to predict the occurrence of the squeal. Beside that there is another necessity to solve stick-slip by using one equation of motion in order to simply changing the parameters at low frequency and find the relation between friction-relative velocities and use it to represent the contact between the surfaces in FEM. This will enable to study the motion in two directions and observed the effect of changing the coefficient of friction on the motion.

2.1 Introduction

This chapter reviews the most important research works carried out about brake squeal and factors affecting it. Understanding brake squeal and friction-induced noise requires complicated analysis due to complexity of brake system. The chapter starts with reviewing experimental works conducted to analyze disc brake squeal. The next section focuses on finite element modelling of squeal by using modal participation method and complex eigenvalue analysis. The numerical methods which were used to solve friction induced vibration were reviewed in section 2.4. The chapter finished with a brief review of available literature about.

2.2 Experimental analysis of disc brake squeals

2.2.1 Beam on disc technique

Understanding and preventing brake squeal was the main object of previous experimental studies. In a pioneering study, Masayuki and Mikio (1979) used the beam on disc test with dry friction to study the brake noise. Their experimental apparatus used a beam on disc technique with accelerometers to measure the disc brake system vibration. The beam-on-disc consists of a cantilever beam which represents the pad while the rotation disc represents the disc brake rotor. The beam and the disc are pressed against each other by a weight. They classified the friction noise to rubbing and squeal. They found that the noise was caused by the lateral vibration of the rod only. They also found that when the friction coefficient is small the vibration is small for that the rubbing noise has low level. The results showed that the rubbing noise can be changed to squeal noise due to the wear during the sliding work to change the surface roughness. Masayuki and Mikio (1981) studied the effect of contact angel on the squeal using beam on disc system with variable angle of the rod. Their results showed that when the rod angle is in the same direction with the disc rotation, rubbing and squeal occurs and the vibration increases with increasing the rod angle.

Tworzdlo and Oden (1992) studied the instability of friction in a mechanical system. A pin on disc apparatus was used to represent the brake interface surfaces. They investigated that the oscillation of the system is due to mode coupling at high-frequencies and stick slip motion in low frequencies. A jump for the beam occurs in two typical situations: in the case of high amplitude, self-excited oscillation and at the very beginning of the sliding after the static contact of two surfaces (slip after stick). They found that self-excited oscillation occurs when the natural frequencies of the normal and rotational vibration of the slider are close to each other in presence of friction force.

Tuchinda, et al (2001) and Tarter (2004) used pin-on-disc system in order to study how squeal noise can be generated in disc brake. The two components (pin and disc) were coupled together by using coulomb friction. The model showed that instability can occur when one of the natural frequencies of the pin becomes close to the natural frequencies of the disc. Giannini, et al. (2006) used beam on disc system to identify the key parameters controlling the squeal. They showed that the squeal occurs when the frequencies of the individual parts are close to each other. Squeal does not require the stick-slip limit cycle to create and does not generally affect by changing the relative velocity.

Akay, et al. (2009) worked on approaching the experimental setup of brake noise to much simpler model than the commercial disc brake. The model provides a possibility of repeatable measurement of squeal occurrence. This model is consisting of simplified experimental rigs (beam-on-disc), figure 2-1.

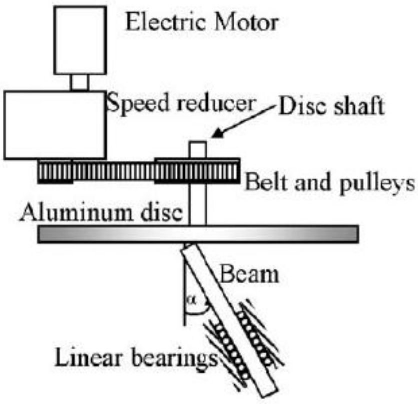

Figure 2-1 schematic of beam-on-disc, Akay et al. (2009)

The cantilever beam is mounted on a sliding platform that moves on two linear bearings, allowing the cantilever beam to be pre-loaded against the disc with a specified normal load. The angel between the beam and the disc is close to 45 degree. This angle is allows the friction force to excite easily the bending vibration of the beam. They found that squeal frequency is always coincident with a natural frequency of the coupled system and not with the frequency of the free rotor (this explains the small discrepancy between squeal frequency and free rotor natural frequency).

2.2.2 Holographic interferometry

Fieldhouse and Newcomb (1991) used a holographic image to measure the displacement of the disc and analyse the free mode of the disc/pad at self-generated noise. They providied visual images of the system in order to understand the mechanism involved, as shown in Figure 2-2. They showed that the entire squeal achieve when the disc in one of the diametral mode. The squeal noise was found to be close to the natural frequency of the brake component.

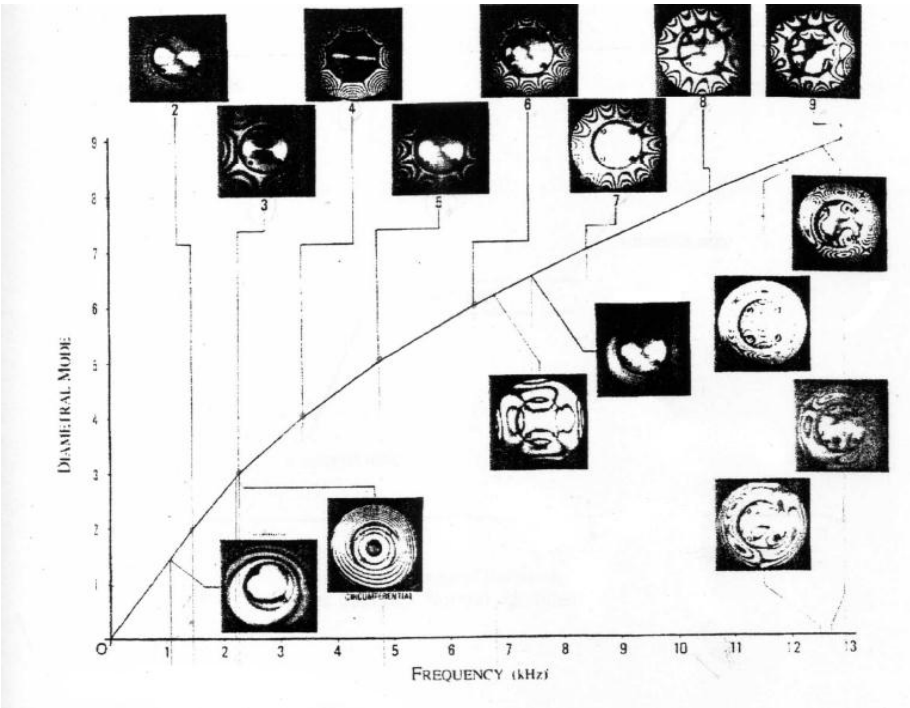

Figure 2-2 Photographs of the holographic reconstruction showing disc mode shape versus frequency, Fieldhouse (1991)

In 1993, Fieldhhous and Newcomb used a double pulsed laser holographic technique, which was developed to allow simultaneous recording of three orthogonal visual images of vibrating brake system. Visual images of vibration characteristics of noisy brake showed the disc to be in bending mode with diametral modes. The pad was seen to vibrate in a variety of modes such as bending, torsion and often a combination of both. The pad and flutter (disc) was shown to make significant contribution to make system noise. The researchers found that the introduction of asymmetry into the rotor was a solution to inhibit the formation of symmetrical diametral mode of vibration and the trendy to generate noise. In 1999, Fieldhouse used technique of holographic interferometry to record the modes of the vibration and found that increasing the contact pressure resulted in increasing frequency over a specific range. The research showed that the preferred excitation frequency of any disc brake may be related to the free mode frequency of the disc. The tendency to generate noise frequency often less than the free mode frequency of the disc for the same mode order. The mode shape under the pad will be compressed if two antinodes are held, causing the free antinodes to expand and results in a lower frequency. If one anti-node is held below the pad it will expand in order to occupy the space available. This causes the free antinodes to compact and generate higher frequency. An increase in pad length would not significantly affect the pad/rotor interface pressure distribution. The experiment showed that the maximum pad effective length is varying between 80% -100% of full pad length.

Talbot and Feildhous (2000) captured holographic images and created animated 3-dimensional images of brake system during the squeal. The results showed that the displacement variation of the disc at fix radius was a sin wave during the squeal. Fieldhouse and Newcomb (2001) analysed the noise by using holographic interferometry of two brake system with different volumes. The noise occurs as a result of coupling natural frequency of the individual brake parts when those frequencies are close together. The researchers indicated that anti-node positioned at the centre of the pad at higher frequency whereas it is a node in the case of lower. Filnt and Hald (2003) studied the existence and direction of travelling waves in the squealing disc brakes by using acoustic holography. Acoustic holography measures the radiation sound pressure. They used the microphone to measure the sound during the squeal. The results showed that the nodal position rotated 180 degree in clockwise direction during one period of oscillation. This means that there is a travelling wave in the opposite direction of rotation of the disc and the motion of the node is not due to the rotation of the disc.

2.2.3 Pulse electronic speckle pattern interferometry

The works based on holographic interferometry technique was continues until another optical technique, electronic speckle pattern interferometry (ESPI), was developed. ESPI device automatically fire a laser and provide the complete deformation map of the component under test and can capture the squealing signal. Dantec Dynamics Company used EPSI to study the brake squeal which was illustrated in Figure 2-3. They measured the brake disc while it was rotating with the pulsed ESPI system. The result indicated that three dimensional ESPI was very useful for the analysis of the dynamic behaviour of disc brake in highly dynamic processes.

Figure 2-3 Dantec Dynamics Company apparatus, 3D Pulse ESPI system, http://www.dantecdynamics.com/Default.aspx?ID=1603

Chen et al. (2000) used EPSI technique to obtain the mode shapes of a disc brake when it was squealing. This work investigated the radial mode and friction process which contribute in brake squeal noise. The researchers showed that when the system has higher vibration amplitude, it will have a higher tendency to be operated in an unstable region. If the transverse mode of the rotor has the same resonant frequency of radial mode the squeal noise will amplify. René et al (2001) used camera beside the ESPI to capture the disc mode shape as René et al (2003) used the same apparatus on drum brake.

2.2. 4 Laser doppler vibrometer (LDV)

McDaniel et al (1999) applied a LDV to scan the disc at the normal velocity of a shaker-excited stationary brake system and they found that the resonant behaviour was associated with squeal mechanism. The LDV is an instrument that was used with a non-contact to measure the vibration of the disc surface. The laser beam from the LDV was directed to the surface of disc, and due to the motion of the disc surface the laser doppler frequency changed, however the vibration amplitude and frequency were extracted from this alter. They understand from the findings that the rotor was responsible for the most noise and primary radiator to the sound since the rotor area is much larger than other component. These methods have two advantages, it does not require difficult task in the laboratory and it allows measuring the frequency on a stationary rotor. Svend et al. (2002) applied LDV on the brake and they found additional benefit of this method that the frequency range of measure can be quite high. This includes high spatial resolution in the measurement and faster than ESPI. Chen et al. (2002) used LDV to measure the rotor diametral. Their result indicated that the coupling of the in-plane rotor modes and diametral mode of the rotor was responsible for the generation of high frequency squeal. Claus

Thomas (2003) carried out vibration analysis of squealing brake system under running condition. These experimental approaches used accelerometer, laser-interferometry and acoustic camera. The diametral mode shape with zero pad pressure was investigated for entire brake systems at different frequencies.

2.2.5 Reduce brake squeal method

Join Flint 2003 analysed the effect of a rubber coated steel plate- a shim- on the backing plate of a brake pad during the brake squeal. The results illustrate that the thick constrained shims layer gives high damping at low frequencies, while thin layer give high damping at high frequencies. Kung, S. - W. et al (2000) made many modifications on disc brake system to reduce the brake squeal by focusing on solution to reduce the stiffness of the rotor. This is accomplished by a reduction in the young’s modulus of the rotor material. The simple modification was done by changing the amount of the graphite in the cast iron to shift the natural frequency of the rotor, so the young’s modulus of the rotor is 96GPa as opposed to 120 GPA. The result showed that changing the rotor material may decouple the modal interaction and eliminate dynamic instability. Fieldhouse and Beveridge (2000) studied the effect of non-chamfered and chamfered pads on the frequency. The elastic fix shims was proven as useful at higher frequencies over 6000 Hz but it was not so effective at the lower frequencies of around 2000Hz. They investigated the effects of the calliper angel, pressures and temperatures on the brake squeal for two types of friction material. From the result it is seen that the brake squeal become quite at angle 166 degree and above. Gouya and Nishiwaki (1990) found that in every doublet mode there is a critical contact span angle. Homffman CT (1988) studied the reduce of brake squeal by using a viscoelastic material (damping material) on the back of the back plate of the pads and found it can effect in reducing squeal when the pad in bending vibration.

2.3 Analysis of squeal by using finite element method

The finite element is the tool for modelling disc brake system and providing a new insight into the problem of brake squeal. FEM allows accurate representation of complex geometries and boundary condition. The finite element method has been employed by the researchers in the brake squeal study. One of the uses of finite element method is to investigate the modes and the natural frequency of the brake rotor with complex eigenvalue then they used modal participation method in order to analyse the contribution of each part of the brake system in generating the squeal. The third section is analysing the squeal by using beam-disc system. Then study the two direction response due to the self-excited vibration.

2.3.1 Predicting squeal with complex eigenvalue

Liles's (1989) used solid elements to build his finite element model for each brake component and carried out modal testing on these components. Friction was added into the model as a geometric coupling. A complex eigenvalue formulation was derived for the system. The complex eigenvalue was constructed by solving the equation of the motion and consist of two parts. The first is real indicating to the stability while the second was imaginary indicating to the damped frequency. He constructed the friction stiffness matrix using relative displacements between mating surfaces. Kido et al. (1996) studied the relation between the squeal propensity and the ratio of the eigenvalues. They showed in the finite element results that higher ratio of eigenvalue increased the tendency to squeal.

Blashchke et al (2000) used the complex eigenvalue analysis to detect the unstable mode of the system. They modelled the rotor and pad interface to create the matrix of the contact and used it inside the equation of motion. The contact matrix made both the mass matrix and the stiffness matrix to be a non-symmetric, so that the eigensolution became complex. A cure (one of the brake parts) was proposed joining the system in order to add some lumped masses to the drum. The benefit of that method was to add the effect of the braking pressure, rotation velocity and temperature to this analysis. Nack (2000) used complex eigenvalue in his study on brake squeal. The aim of complex eigenvalue was to shift those complex eigenvalues that appear in the right-hand side of the plane (root locus diagram) to the left-hand side of the same plane. He also presented a method to add the friction stiffness to his vehicle modal inside FE software and use eigenvalue analysis to determine the necessary condition for the system to become unstable and grow into a state of limit cycles.

Kung et al. (2003) and Greg (2003) used complex eigenvalue to investigate the effect of contact friction on the squeal. The results showed that major noise frequencies are higher than 5 kHz. The cause was mostly due to the involvement of tangential modes. The shear mode would contribute to squeal problem at frequency 12.5 kHz (that mode is outside the audible mode). If the diametral mode be coincided with the longitudinal mode, the noise would line up. Zhang et al. (2003) found by using complex eigenvalue that not all the unstable mode squeal but an unstable mode was just one necessary condition for squeal. Their result also showed that if damping included in the model, some unstable modes became stable while some modes appear at very low friction coefficient. Chung et al. (2003) presented a new process to analyses brake squeal by applying modal domain analysis using FEM to provide a new method instead of complex eigenvalue called virtual design process. Kung et al. (2003) used complex eigenvalue to analyse disc brake squeal. The brake pressure was iterated form 0.69MPa to 2.76MPa (brake pressure range) and the result was plotted in complex plane. Material damping and friction damping between the lining material and the rotor was added to the system. Complex eigenvalue was found in the same previous iteration pressure and it was found that the number of unstable mode was decreased. The researchers showed that the major noise frequency appeared at a frequency higher than 5 KHz due to involve tangential mode and shear mode.

Lou (2004) used complex eigenvalue to study disc brake squeal. He was applied coulomb's friction at the contact interface and produced unsymmetrical contact matrix which yield complex eigenvalue. His analysis showed that any complex eigenvalue with a positive real part indicated an unstable mode, which may results in squeal. In his work Lou searched for the mode responsible about the squeal and the percentage of the propensity (eigenvalue with positive real part). He found that the bigger propensity appeared with higher unstable mode. Cao et al. (2004) modelled the disc brake component using FE. The disc was modelled as a thin plate. The pads mate with different spatial area as the disc rotates and vibrates. The disc brake and the stationary component are studied as a moving load problem. Due to the asymmetry of the real brake there are no double frequencies in the finite element model of the real disc. A linear complex value was derived for the friction-induced vibration of the disc brake in order to present the unstable frequency.

Joe et al. (2007) used complex eigenvalue to investigate the dynamic instability of the brake system. If the real part of an eigenvalue is positive, the corresponding imaginary part was thought to be possible squeal frequency. The analysis indicates that modal coupling is responsible for disc brake squeal due to the friction force. The friction is introduced by altering the system stiffness matrix to be unsymmetrical. Higher friction coefficients always tend to make two modes merging and form unstable complex mode. Increasing the stiffness of the lining material causes the system to become more unstable. Increasing the length of the pad causes the system to become more unstable, as increase the thickness of the lining material. Increasing the disc thickness, the unstable mode above 10000Hz become unstable. The squeal at 5000Hz and below is due to the modal coupling while above 10000Hz is due to the modal splitting. Fritz et al. (2007) used FEM to compute complex eigenvalue technique. They found that by adding damping to the system the real parts of eigenvalue get shift to the negative value. The results showed that when the system is stable and the friction coefficients increase the real part remains zero but the frequency of the stable mode tend to get closer.

Dai et al. (2008) suppressed brake noise by using FE and found positive complex eigenvalue which produce unstable modes where the positive eigenvalue indicate the propensity towards generation of squeal noise. The researchers developed a sufficiently reliable brake dynamic modelling tool that could be applied to evaluate the effects of pad structural design parameters on brake squeal generation and avoid trial-and-error approaches to address brake noise concerns, which are time consuming and costly. The authors proposed theory based on a double-pin on disc formulation as shown in Figure 2-4.

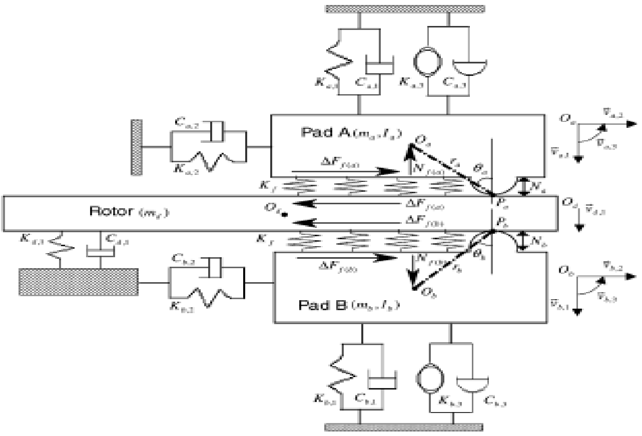

Figure 2-4 Schematic of the proposed lumped parameter model of the rotor–pad assembly, Dai, Y. et al (2008)

In this proposed contact model, the pads are pivoted against a pair of rigid contact pins designated as Pa and Pb. The effect of the pin radius from pivoted centre on the degree of instability was studied. Increasing the radius will increase the degree of instability. The effect of contact angle between the pin and the disc face Ɵa and Ɵb affected by various factor, including length of the lining, chamfer geometry and nature of the load distributed. The effect of friction coefficient of the lining rotor was investigated for inner and outer pad. As friction increases, some of the modal frequencies start to merge toward each other. Figure 2-5 shows the instability versus friction coefficient of inner and outer pad. The propensities of squeal increasing with increase friction coefficient because the higher coefficients of friction cause the variable friction force to excite greater number of unstable modes.

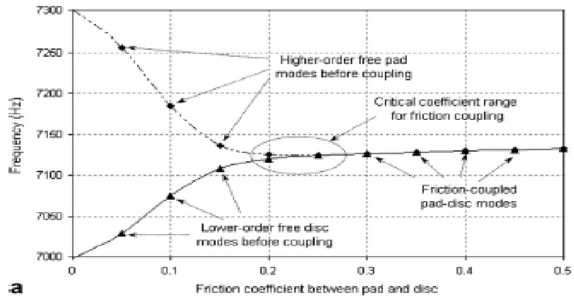

Figure 2-5 Friction coefficient as a function for the frequency, Dai, Y. et al (2008)

2.3.2 Predicting squeal with modal participation method

Kung et al (2000) used modal participation method for calculating the brake component participation percentage in generating the squeal, in order to define the system squeal mode shape. Component participation was made for each part of the brake system in order to conduct each part contributes in brake squeal. From the results, it was seen that the rotor was one of the brake parts that has major responsibility for brake squeal. NASTRAN Software was used to calculate the modal participation factor based on MAC (Modal Assurance Criteria) Algorithm. The purpose of their work was to demonstrate a systematic approach of modal participation analysis as a post proceeding tool for the complex eigenvalue method. The authors found that the first circumferential (tangential) mode of the rotor was very close to the squeal frequency and he suspected that the circumferential mode causes the squeal. Kung et al. (2000) computed the modal participation factors of brake component to find a ways of suppressing unwanted modes and thus reducing the possibility of a particular squeal frequency.

2.3.3 Study the effect of asymmetric by using FEM

Ghesquiere and Castel (1991) represented the disc and the two pads by three degree of freedom system model including the contact pressure in order to get the natural frequency of the system. The friction was applied between the pads and the disc. The effect of the friction led the mode shape to have a different aspect, and lose its symmetry. The equation of the motion had mass and stiffness matrix, in case of adding friction or changing the brake system symmetry shape, the stiffness matrix will lose it symmetry. The effect of the friction led the mode shape to have a different aspect, and they lose their symmetry. Their result showed that the frequency grows faster after third diametral mode because the contact stiffness counter of the disc displacement and thus the system stiffness energy grow. When the friction coefficient is increased from 0 to 0.7, the coupling mode shapes that appear are not totally symmetric or totally anti-symmetric.

Lee and Yoo at (2001) analysed the effect of changing shoe from uniform cross-section to non-uniform cross-section on the brake squeal. In this study, the drum and the shoes are assumed as a uniform ring and non-uniform arches respectively. The non-uniform cross-section built by changing the shapes of the shoes partially. The influences of brake design parameters upon the squeal investigated by theoretical analysis. The effect of this change verified through noise dynamometer tests. The effect of the asymmetry of the drum, which built by additional mass, was presented. The increase of the cross-section area and the decrease of the bending stiffness of the shoe are advantageous to the reduction of the squeal. The lumped masses were attached to the drum for the asymmetry, and the influences of the masses were analysed with the coefficient of friction of 1.0 which is much higher than that of the critical value 0.37.

Lou and Wu (2003) studied the disk brake squeal due to unstable friction-induced vibration using the ABLE algorithm FE software. Coulomb Friction and normal displacement were applied in the area of contact for that the stiffness matrix becomes unsymmetrical. Unsymmetrical matrix led to generate complex eigenvalue. The researchers found that when brake squeal occurs, the rubbing surfaces do not stick to each other and the relative sliding speed is always unidirectional. The eigenvalues and the eigenvectors are found in each individual component by the FEM. The friction springs element was applied between the nodes at the pad–rotor interfaces to simulate the frictional mechanism. Asymmetric distribution of the pressure between the rotor and piston-pad interface made Abu Bakar et al. (2003) to study about the contact pressure distribution. The asymmetry of this pressure is due to the friction force between the surfaces. The authors made modification on the pad and/or at the piston and the back plate to make the life of the pad longer, reduce the wear and eliminate the squeal. The pressure distribution at rotor and piston pad interface was examined with different rotor speed in order to achieve uniform pressure distribution. The interface pressure distribution of the pad under the piston was conducted with three different rotation velocities. The FE software showed when the rotor at the rest the pressure distributed is symmetric about the centre line of the pad while when the disc rotates the pressure distribution no longer symmetric and the high pressure occurs at the leading side of the pad. Increasing the thickness of the back-plate could produce desirable pressure distribution. It is found that by making right connection between the piston and pack plate the