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EVALUATION OF AN AUTOMOTIVE WIPER NOISE AND VIBRATION CHARACTERISTICS USING NUMERICAL APPROACH

(PENILAIAN KE ATAS CIRI –CIRI HINGAR DAN GETARAN PENGELAP AUTOMOTIF MENGGUNAKAN KAEDAH BERANGKA)

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TAJUK PROJEK : **EVALUATION OF AN AUTOMOTIVE WIPER NOISE AND VIBRATION CHARACTERISTICS USING NUMERICAL APPROACH**

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ABSTRACT

EVALUATION OF AN AUTOMOTIVE WINDSCREEN WIPER NOISE AND VIBRATION CHARACTERISTICS USING NUMERICAL APPROACH

(Keywords: Automotive wiper, chatter, noise & vibration, finite element, suppression approach)

As modern passenger cars become increasingly quieter and comfort, automotive windscreen wiper noise and vibration become more noticeable. As a result of the market information survey, most complaints about the wiper concern operation noise. Wiper vibration and noise is classified into three main categories namely, squeal noise, chattering, and reversal noise. Squeal noise is a high-frequency vibration of about 1000 Hz. Chattering noise is a low-frequency vibration of 100Hz or less and reversal noise is an impact sound with a frequency of 500 Hz or less produced when the wiper reverses.

Typically, noise and vibration study of the automotive windscreen wiper has been carried out by experimental, analytical and numerical approaches. This report describes evaluation of noise and vibration that generated by an automotive windscreen wiper using numerical approach via finite element method. In doing so, two types of test are conducted i.e. modal testing for individual wiper components and noise and vibration test to identify noise category for a selected passenger car windscreen wiper. Later, a 3-dimensional (3D) finite element (FE) model of the windscreen wiper assembly is developed. This FE model is then validated at the component level using modal analysis in order to ensure that dynamic characteristics of the FE model close to a real windscreen wiper.

In order to evaluate characteristics of noise and vibration of the windscreen wiper, complex eigenvalue analysis that made available in ABAQUS is employed. It is found that the windscreen wiper generates noise at frequency around 11 Hz which is identified as chatter and the predicted frequency is fairly close with measured frequency obtained in the experiment. This chatter noise is dominated by bending mode of the wiper blade. Having found the characteristics of the windscreen wiper noise, several structural modifications are proposed to the rubber blade and simulated once again. There are three modifications that capable of preventing noise and vibration in the windscreen wiper. This finding could help car makers to design quiet and effective windscreen wiper and in turn to produce quieter and comfort passenger cars.

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ABSTRAK

PENILAIAN KE ATAS CIRI –CIRI HINGAR DAN GETARAN PENGELAP CERMIN AUTOMOTIF MENGGUNAKAN KAEDAH BERANGKA

(Kata kunci: Pengelap automotif, chatter, hingar dan getaran, kaedah unsur terhingga, pendekatan pengurangan)

Oleh kerana kenderaan penumpang moden masakini semakin senyap dan selesa, hingar dan getaran yang dihasilkan oleh pengelap cermin automotif semakin mendapat perhatian. Hasil daripada kajian pasaran menunjukkan bahawa kebanyakan aduan dari pengguna menjurus kepada isu hingar pengelap cermin. Hingar dan getaran pengelap cermin boleh dikelaskan kepada tiga kategori iaitu hingar nyaring, hingar *chatter* dan hingar balikan. Hingar nyaring adalah getaran frekuensi tinggi pada 1000 Hz. Hingar *chatter* merupakan getaran frekuensi rendah pada 100 Hz atau lebih rendah manakala hingar balikan adalah bunyi hentaman pada frekuensi 500 Hz atau kurang ketika pengelap membalik.

Lazimnya, kajian terhadap getaran dan hingar pengelap cermin automotif dijalankan secara pendekatan ujikaji, analitikal dan kaedah berangka. Laporan ini menerangkan penilaian ke atas hingar dan getaran yang dijana oleh pengelap cermin menggunakan kaedah berangka melalui kaedah unsure terhingga. Untuk itu, dua tahap ujikaji dijalankan iaitu ujikaji modal bagi setiap komponen pengelap cermin dan ujikaji hingar dan getaran bagi mengenalpasti kelas hingar bagi pengelap cermin kenderaan penumpang yang dipilih. Seterusnya, sebuah model pengelap cermin tiga dimensi unsur terhingga dibina. Model ini akan ditentusahkan bagi setiap komponen melalui analisis modal bagi memastikan cirri-ciri dinamiknya setara dengan komponen yang sebenar.

Bagi menilai ciri-ciri hingar dan getaran pengelap cermin, analisis nilai eigen komplek yang disediakan oleh perisian ABAQUS akan digunakan. Hasil daripada analisa, pengelap cermin menghasilkan hingar pada frekuensi sekitar 11 Hz yang mana ianya dikelaskan sebagai hingar *chatter* dan keputusan ini hampir sama dengan frekuensi yang dirakamkan di dalam ujikaji. Hingar chatter ini didominasi oleh mod lenturan bagi bilah pengelap. Setelah mengetahui ciri-ciri hingar pengelap, beberapa pengubahsuaian struktur terhadap bilah pengelap dicadangkan dan dianalisis semula. Didapati tiga pengubahsuaian yang dicadangkan berupaya untuk menghalang berlakunya hingar dan getaran pada pengelap cermin. Penemuan ini mungkin berguna kepada pengeluar kenderaan bagi merekabentuk pengelap cermin yang senyap dan berkesan dan seterusnya menghasilkan kenderaan penumpang yang lebih senyap dan selesa.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Windscreen wipers are indispensable components to the maintenance of a safe and comfortable field of vision when driving on rainy days. Today, almost all automobile are equipped with windscreen wiper, often by legal requirement. Clear vision for the car driver is an important prerequisite for safety in road traffic. A conventional wiper as shown in Figure 1.1 generally consists of an arm, pivoting at one end and with a long rubber blade attached to the other (Denso International Products, 2008). The blade is swung back and forth over the windscreen, pushing water from its surface. The mechanical structure of the wiper blades is attached to the arm tips, holds the rubber blade, which drains the water off the windscreen or to smooth the water on the surface of the windscreen in order to create a thin film that allows light to pass through it without refracting or bending as shown in Figure 1.2.

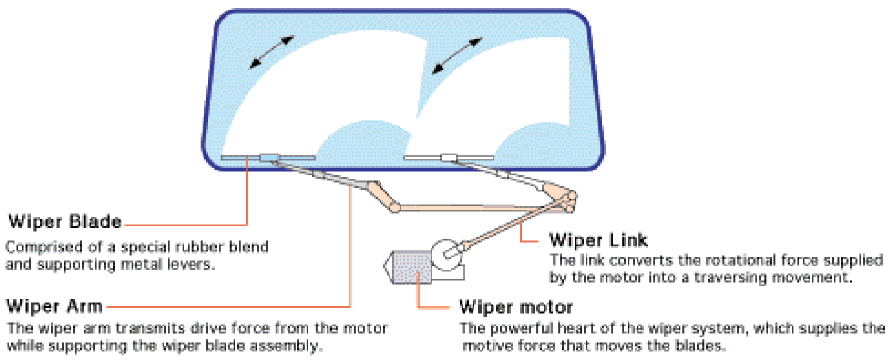

Figure 1.1: Wiper system on a windscreen (Denso International Products, 2008).

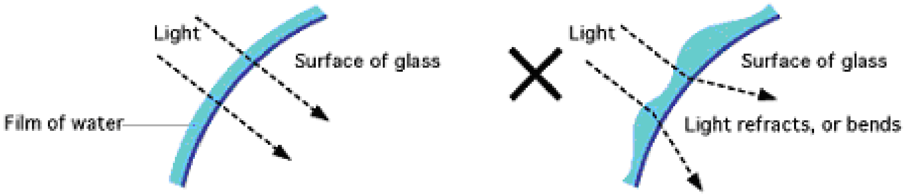

Figure 1.2: Load distribution of a wiper blade (Denso International Products, 2008).

It is very often that the windscreen wiper generates unwanted and annoying noise and vibration. This noise and vibration can be classified into three categories namely, squeal noise, chattering and reversal noise. Squeal noise, sometimes called squeaky noise, is a high-frequency vibration of about 1000 Hz. Chattering or beep noise, is a low-frequency vibration of 100Hz or less. Reversal noise is an impact sound with a frequency of 500 Hz or less produced when the wiper reverses. These types of noise and vibration lead to visual and audible annoyance for the driver and passengers (Goto et al, 2001a).

Numerous studies using analytical, numerical and experimental approaches have been carried out to investigate noise and vibration of an automotive wiper system. Okura et al (2000) performed dynamic analysis of blade reversal behaviour using a 2-dimensional (2D) mechanical model of a wiper system and a spring-mass model of an arm and blade. They, in another work, further studied the dynamic analysis using a complete 3-dimensional (3D) model. Comparison between the 2- and 3- dimensional model for the arm and blade was made and the results suggested the 3D model could simulate the reversal behaviour of the wiper system more accurately than the 2D model (Okura and Oya, 2003).

The squeal noise reduction using a mathematical model has been proposed in (Goto et al, 2001a; Goto et al, 2001b). In their studies, physical properties and design of the blade were varied. In order to compliment the predicted results, experiments on squeal noise were also carried out to verify the effectiveness of the proposed material and design changes. A combined approach to study chatter vibrations for a wiper system has also been performed in (Grenouillat et al, 2002). Wiper motion tests were carried out on a developed test rig. Different attack angles and pressure were used and their effect on the wiper motion was observed. They also developed a 2D mathematical model to demonstrate the influence of the geometrical configuration of the wiper system on the generation of unstable motion. The application of dither control to stabilize squeal noise in the wiper system has been introduced in (Stallaert et al, 2006). A finite element

(FE) model was developed in order to support the optimization of the control configuration. The study showed that with a proposed dither control, wiper squeal noise was effectively suppressed. Chevennement et al (2007) developed a FE model to study dynamic instability of a flexible wiper system. Different values of arm forces and attack angles of a rubber blade were selected and simulated to examine their effects on the vibration response of the wiper. The predicted results were close to those obtained in the experiments.

1.2 Objectives of research

From the aforementioned studies, it is found that none of them investigates wiper vibration using FE method through complex eigenvalue analysis. Therefore, the objectives of this project are:

i) To develop a validated finite element model of a real windscreen wiper and analyse its stability using complex eigenvalue analysis

ii) To propose and evaluate possible suppression approach through structural modifications that can prevent or reduce noise and vibration of the wiper system

1.3 Research methodology

The methodology consists of four major elements:

a) Review of noise and vibration of an automotive wiper

Firstly, a thorough study on proposed noise and vibration mechanisms are made from various published sources such as journals, books and magazines. Those proposed mechanisms would be examined later in order to assess their contributions towards noise and vibration of a wiper.

b) Experimental approaches

Two stages of experiment will be conducted: i) modal testing in order to capture dynamic behaviour of the windscreen wiper components and ii) noise and vibration of the windscreen wiper in order to identify type of noise that is generated in a selected passenger car. These measured data will then be used to verify predicted results those found using finite element method in the next stage of the project.

c) Development of a finite element model

Finite element (FE) method is useful to determine noise and vibration characteristics of a wiper. The FE model will be developed and simulated using commercial FE software package namely, ABAQUS v6.6. Various designs of a wiper can be easily modeled and simulated. It is a cost and time efficient compared to a developing prototype, which requires quite a high cost to develop and fabricate. The developed FE model will be then validated in terms of natural frequency and its associated mode shape at component level. Vibration and noise test of the windscreen wiper will be conducted and to identify type of wiper noise. Later, complex eigenvalue analysis will be performed on the FE model in order to predict stability of the wiper. Results of the prediction will be then compared with those find in the tests.

d) Development and evaluation of suppression method

Suppression method should able to reduce and/or eliminate noise and vibration of the wiper up to acceptable level. Based on the predicted results, various suppression methods will be identified and simulated. Suppression method can be either modifying the wiper blade structure and/or changing the mechanical properties of an existing wiper rubber. All proposed suppression would be then evaluated through simulation in order to examine their effectiveness.

1.4 Report organization

The report is organized into six chapters. **Chapter One** deals with the description of research background, objectives and methodology. Chapters Two to Five are actually technical papers that are published in conference proceedings and journals at both national and international levels.

Chapter Two: An experimental investigation into noise and vibration of an automotive wiper

Chapter Three: Modelling and simulation of automotive wiper noise and vibration using finite element method

Chapter Four: Finite element analysis of windscreen wiper chatter noise and its suppression approach through structural modifications

Chapter Five: Complex eigenvalue analysis of windscreen wiper chatters noise and its suppression through structural modification

Chapter Six summarises the results and provides conclusions of the present work. Recommendations for further work are also presented in this chapter.

CHAPTER 2

AN EXPERIMENTAL INVESTIGATION INTO NOISE AND VIBRATION OF AN AUTOMOTIVE WIPER

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ABSTRACT

As modern passenger cars become increasingly quieter, wiper operation vibration and noise become more noticeable. As a result of the market information survey, most complaints about the wiper concern operation noise. Wiper vibration and noise is classified into three main categories namely, squeal noise, chattering, and reversal noise. Squeal noise is a high-frequency vibration of about 1000 Hz. Chattering noise is a low-frequency vibration of 100Hz or less and reversal noise is an impact sound with a frequency of 500 Hz or less produced when the wiper reverses. In this paper, we experimentally investigate vibration and noise of a passenger car's wiper. First, we determine natural frequencies of a wiper using modal testing. Later, noise and vibration characteristics are observed during wiper operation at the dry and wet conditions. Wiper noise and vibration is also examined at three different speeds, i.e., slow, moderate and fast.

Keywords: wiper; vibration; noise; passenger car, wiping speed

INTRODUCTION

Windscreen wipers are indispensable components to the maintenance of a safe and comfortable field of vision when driving on rainy days. A conventional wiper system as shown in Figure 1 comprises an electric motor and a linkage mechanism which converts the rotational movement of the motor into the back and forth motion of the wiper arms. The mechanical structure of the wiper blades is attached to the arm tips, holds the rubber blade, which drains the water off the windscreen or to smooth the water on the surface of the windscreen in order to create a thin film that allows light to pass through it without refracting or bending as shown in Figure 2.

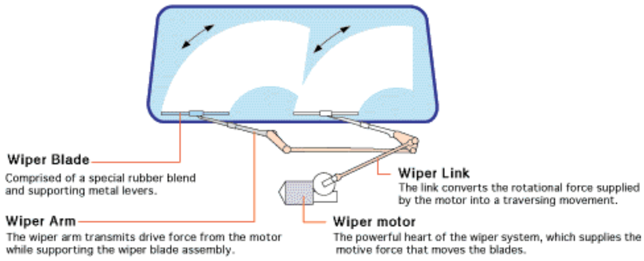


FIGURE 1 Wiper system on a windscreen (taken from Denso Product. Co.)

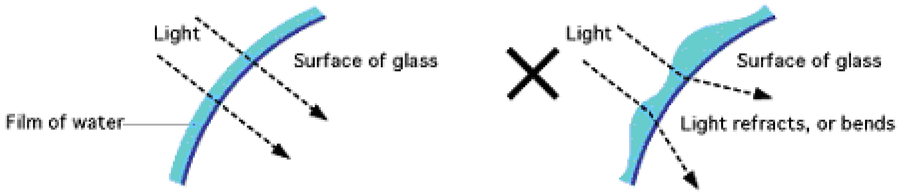


FIGURE 2 Load distribution of a wiper blade (taken from Denso Products Co.)

The purpose of a wiper system is to ensure a clear field of vision by wiping the windscreen clear. However, it is often that the wiper system generates unwanted noise and vibration. Goto et al. (2001a) classified noise and vibration in the wiper system into three groups, namely, squeal noise, chattering and reversal noise. Squeal noise, sometimes called squeaky noise, is a high-frequency vibration of about 1000 Hz. Chattering, or beep noise, is a low-frequency vibration of 100Hz or less. Reversal noise is an impact sound with a frequency of 500 Hz or less produced when the wiper reverses. These types noise and vibration phenomenon lead to visual and audible annoyance for the driver and passengers. Visual of deterioration effects such as streaking, jumping and uneven blade pressure are depicted in Figure 3.

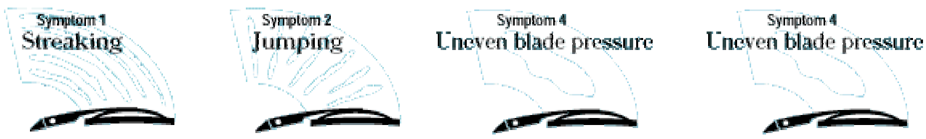


FIGURE 3 Signs of wiper deterioration visible on the front windscreen (taken from Denso Product Co.)

Numerous studies, using numerical and/or experimental approach, have been carried out to investigate noise and vibration of an automotive wiper system (Okura et al. 2000, Goto et al. 2001a, Goto et al. 2001b, Grenouillat and Leblanc 2002, Okura and Oya 2003, Stallaert et al. 2006, and Chevennement et al. 2007). Okura et al. (2000) studied dynamic analysis of blade reversal behaviour using a three-dimensional mechanical model of a wiper system and a spring-mass model of an arm and blade were developed. From these two models they showed that by modifying the maximum rubberneck rotational angle and the rubberneck rotational spring constant reversal impact force could be reduced. They also showed that the reaction force at the top and bottom reversal points could be adjusted by modifying the arm head twist angle. In 2003, Okura and Oya extended their studies considering a complete 3-dimensional model. Comparison between 2D and 3D model for the arm and blade was made and they commented that the 3D model could simulate the reversal behaviour of the wiper system more accurately than 2D model.

Goto et al. (2001a, 2001b) investigated squeal noise reduction using a mathematical model. From the proposed model, material physical properties and design of the blade were varied and they found that those have significant contribution to the reduction of squeal noise. Experiments on squeal noise were also carried out to verify the effectiveness of the proposed material and design changes. Grenouillat and Leblanc (2002) used combined approach to study chatter vibrations for a wiper system. Wiper motion tests were carried out on a developed test rig. Different attack angles and pressure were used and their effect on the wiper motion was observed. They also developed a 2-dimensional mathematical model and used it to demonstrate the influence of the geometrical configuration of the wiper system on the generation of unstable motion. From both approaches they concluded that attack angle and pressure contributed significant effects on the unstable motion (chatter).

Stallaert et al. (2006) employed dither control to stabilize squeal noise in the wiper system. A finite element model was also developed in order to support the optimization of the control configuration. They showed that with a proposed dither control, wiper squeal noise was effectively suppressed. Chevennement et al. (2007) developed a finite element (FE) model to study dynamic instability of a flexible wiper system. The FE model was validated by experimental tests with different value of arm forces and attack angles of a rubber blade. They found that the predicted instabilities were close to those obtained in the experiments.

This paper attempts to investigate experimentally noise and vibration characteristics of a passenger car's wiper system. First, natural frequencies of a wiper system at free-free boundary condition are determined using modal testing. Then, noise and vibration characteristics are observed during wiper operation at the dry and wet conditions with different wiping speeds.

MODAL TESTING

The experimental study of structural vibration has made significant contributions for better understanding in vibration phenomenon and for providing countermeasures in controlling such phenomenon in practice. Typically, experimental observations are always to reach two-fold objectives (Ewins, 1984):

- Determining the nature and vibration response levels
- Verifying theoretical models and predictions

The first measurement objective is referred to as a test where vibration forces or responses are measured during structure normal service environmental operation while the second is a test where the structure or component is vibrated with a known excitation. The second test is much more closely carried out under control conditions and this type of test is nowadays known as modal testing or experimental modal analysis (EMA). In this paper, modal analysis is performed at free-free boundary condition for the blade and the primary yoke whilst at fixed boundary condition for the windscreen. The hammer test method is used to determine natural frequencies of those components. In doing so, a Kistler Type 9722A500 impact hammer is used to produce the excitation force while a Kistler Type 8636C50 uni-axial accelerometer is fix-mounted onto the tested components. Figure 4 shows overall set-up of the experimental modal analysis.

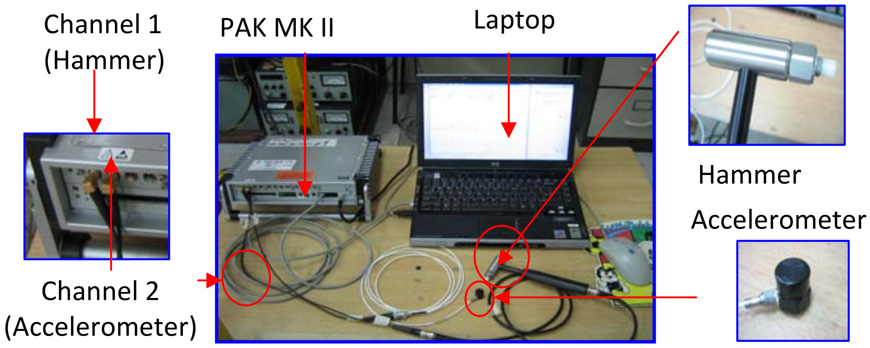


FIGURE 4 Experimental setup for modal testing

From the modal testing it is found that the blade, the primary yoke and the windscreen has six, three and five distinct natural frequencies, respectively within 1 kHz range as given in Table 1. It is seen that those three components have quite similar natural frequencies especially for the blade and the windscreen. In disc brake squeal studies, Kinkaid et al. (2003) commented that one of possible mechanisms for squeal to generate was due to mode coupling, which two different modes occur at the same frequency. Thus, it is interesting to see whether squeal noise is generated during the wiper operation in this work.

TABLE 1 Natural frequencies of the wiper system

Component	Mode 1(Hz)	Mode 2(Hz)	Mode 3(Hz)	Mode 4(Hz)	Mode 5(Hz)	Mode 6(Hz)
Rubber blade	44	130	242	388	648	775
Primary yoke	40	148	734	-	-	-
Windscreen	100	242	384	643	767	

EXPERIMENT ON WIPER NOISE AND VIBRATION

The measurement set-up is shown in Figure 5, where two uni-axial accelerometers are attached to the primary yoke. The wiper used in the experiments is of the uniblade type that typically found in the PROTON cars. Noise and vibration measurements of the wiper are carried out at two environmental conditions: wet and dry, and are measured at three different speeds of 1.8, 2.5 and 2.8 rad/s.

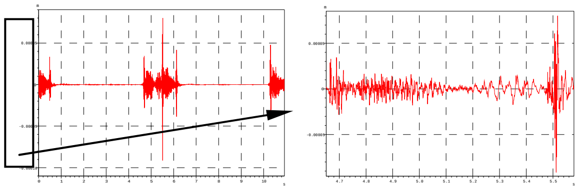
FIGURE 5 Setup for noise and vibration measurement

For a rotational speed of 1.8 rad/s and at wet condition, acceleration response is shown in Figure 6(a). It is seen from the figure that high vibration amplitude is occurred rightly at the beginning and end of the wiper stroke (see overall figure). In the middle of the stroke, the vibration amplitude is lower than that at the start and end of the stroke (see close-up). The vibration amplitude is higher at the beginning and end of wiper stroke may due to two reasons: stick-slip and/or negative velocity-friction characteristic mechanisms (Grenouillat and Leblanc 2002). There is no idle time after one complete stroke for rotational speeds of 2.5 and 2.8 rad/s compared to 4s idle time for rotational speed of 1.8

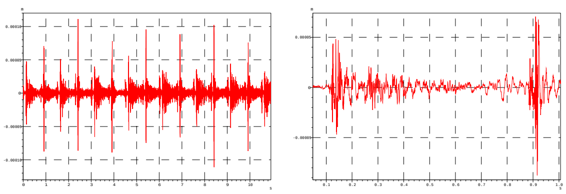
rad/s. This vibration characteristic is seen similar for another two rotational speeds as shown in Figures 6(b) and 6(c). It seems to suggest that the results are concurred with the findings of Goto et al. (2001) where they stated that noise could easily be generated before and after wiper stroke as shown in Figure 7.

When the wiper is operated at dry condition, the vibration characteristics as shown in Figure 8(a) ~ 8(c) are almost identical to those found during wet condition except in the middle of wiper stroke. It is found that in this particular area, the vibration amplitude is quite small compared to that during the wet condition. This suggests that water film that sticks on the windscreen during wet condition can potentially disturb rubber blade motion by separating rubber blade and windscreen interfaces and hence produces a vibration. This need to be examined in details and further investigations are required.

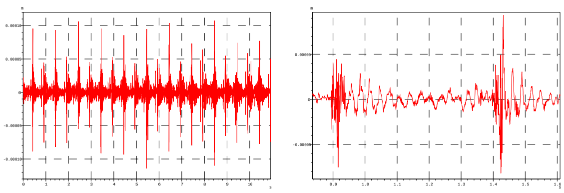
From acceleration responses in Figures 6 and 8 it is found in speed 1 that noise is dominated at frequency of 68 Hz and 36 Hz for the wet and dry conditions, respectively as shown in Figure 9(a). This shows that noise frequencies are higher in the wet condition compared to those in the dry condition. For speed 2, i.e., 2.5 rad/s as depicted in Figure 9(b) noise is generated at dominant frequency of 70 Hz for the wet condition and 36 Hz for the dry condition. This has similar trend with previous speed. Finally for the third speed, 2.8 rad/s the dominant frequency is found at 36 Hz for the wet condition and 32 Hz for the dry condition as shown in Figure 9(c). It seems that for higher rotational speed the noise frequency of the wiper is almost identical. From those measured frequencies, it can be concluded that current wiper system is experiencing chatter noise based on the definition given in previous section. It is also suggested that those identical natural frequencies measured for individual components, which lead to mode-coupling mechanism, are not guaranteed for squeal noise generation since there is no squeal noise generated in current wiper system. It is also observed that the windscreen is experiencing streaking visual deterioration effect.



(a) Speed 1



(b) Speed 2



(c) Speed 3

FIGURE 6 Acceleration responses during wet condition

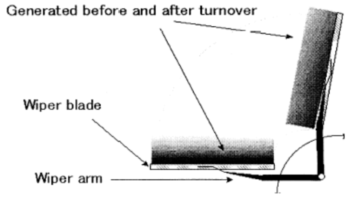
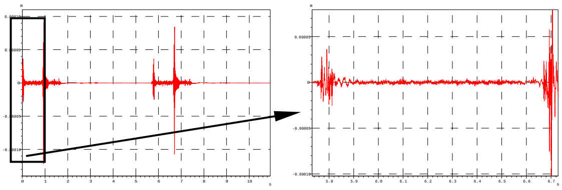
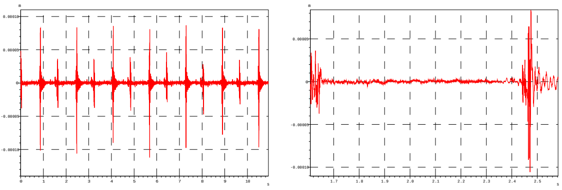


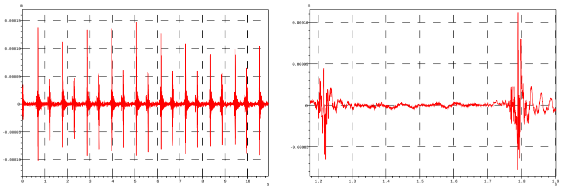
FIGURE 7 Locations of noise generation (Goto et al. 2001)



(a) Speed 1

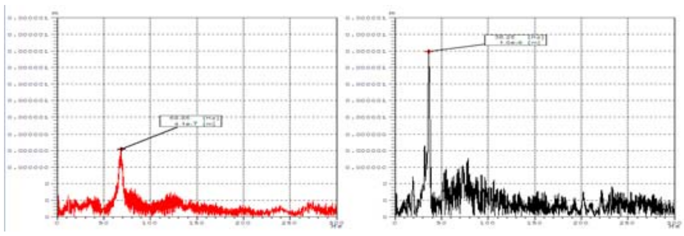


(b) Speed 2

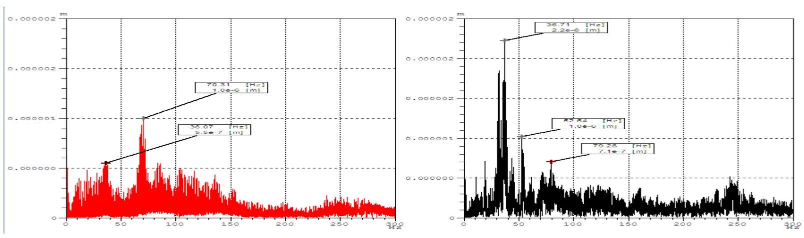


(c) Speed 3

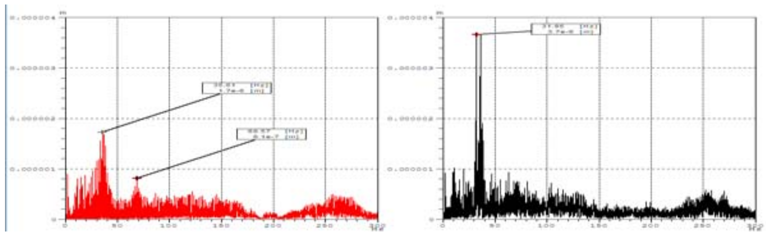
FIGURE 8 Acceleration responses during dry condition



(a) Speed 1



(b) Speed 2



(c) Speed 3

FIGURE 9 Noise frequencies measured from the rubber blade (wet: red colour and dry: black colour)

CONCLUSIONS

The wiper produces a low frequency vibration and noise called chatter, with a frequency below 100Hz, depending on environmental conditions and operating speeds. It is found that, regardless of wet or dry conditions and different wiper speeds, the chattering noise is generated before and after the wiper turnover. However, it seems that the wiper has steady motion in the middle of rotating stroke for the dry condition compared to the wet condition, which non-uniform water films on the windscreen may disturb contact between the rubber blade and the windscreen interfaces that lead to vibration. There is no single squeal noise appears in current investigation and it suggests that closest natural frequencies between wiper components do not guarantee for squeal generation. It is also observed that the windscreen is experiencing streaking visual deterioration effect.

ACKNOWLEDGEMENTS

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REFERENCES

Chevennement, C.R., Dreher, T., Alliot, P., Aubry, E., Lainé, J.P. & Jézéquel, L. 2007. Flexible Wiper System Dynamic Instabilities: Modelling and Experimental Validation, *Experimental Mechanics*, **47,** pp. 201–210.

Ewins, D.J. 1984. *Modal Testing: Theory and Practice,* Research Studies Press, Letchworth.

Goto S., Takashi H., & Oya T. 2001a. Clarification of Mechanism of Wiper Blade Rubber Squeal Noise Generation, *JSAE Review* **22**, pp. 57-62.

Goto, S., Takahashi, H. & Oya, T. 2001b. Investigation of Wiper Blade Noise Reduction Measures, *SAE Technical Paper*, 2001-01-1410.

Grenouillat R. & Leblanc C. 2002. Simulation of Mechanical Pressure in a Rubber-Glass Contact for Wiper Systems, *SAE Technical Paper*, 2002-01-1239.

Kinkaid, N.M., O'Reilly, O.M. & Papadopolous, P. 2003. Review of Automotive Disc Brake Squeal, *Journal of Sound and Vibration*, **267**, pp. 105-166.

Okura, S. & Oya, T. 2003. Complete 3D Dynamic Analysis of Blade Reversal Behavior in a Windshield Wiper System, *SAE Technical Paper*, 2003-01-1373.

Okura, S., Sekiguchi, T & Oya, T. 2000. Dynamic Analysis of Blade Reversal Behavior in a Windshield Wiper System, *SAE Technical Paper*, 2000-01-0127.

Stallaert, B., Doucet, F., Rys, J., Diallo, A., Chaigne, S., Swevers, J. & Sas, P. 2006. Application of Dither Control for Automotive Wiper Squeal, *Proceedings of ISMA 2006*, pp 263-272.

CHAPTER 3

Modelling and Simulation of Automotive Wiper Noise and Vibration Using Finite Element Method

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(Paper presented at 2nd Regional Conference on Vehicle Engineering and Technology 2008, Kuala Lumpur, 15-17 July 2008)

Abstract

As modern passenger cars become increasingly quieter, wiper operation vibration and noise become more noticeable. As a result of the market information analysis, most complaints about the wiper concern operation noise. Wiper vibration and noise is classified into three main categories namely, squeal noise, chattering, and reversal noise. Squeal noise is a high-frequency vibration of about 1000 Hz. Chattering noise is a low-frequency vibration of 100Hz or less and reversal noise is an impact sound with a frequency of 500 Hz or less produced when the wiper reverses. This paper presents numerical studies on noise and vibration of an automotive wiper blade. A 3-dimensional (3D) finite element (FE) model of a wiper blade assembly is developed and then validated at the component level using modal analysis. Complex eigenvalue analysis available in ABAQUS is employed to determine stability of the wiper blade assembly. It is found that predicted results from complex eigenvalue analysis are fairly close to those generated in the experiment.

Keywords: wiper; noise & vibration; finite element; complex eigenvalue; modal analysis

1. Introduction

A windscreen wiper is indispensable device used to wipe rain and dirt from a windscreen. Today, almost all automobile are equipped with windscreen wiper, often by legal requirement. Clear vision for the car driver is an important prerequisite for safety in road traffic. The wiper faithfully keeps the windscreen clear, moving back and forth across the windscreen countless times as they sweep the water away. Traditional windshield wipers are actuated by a single constant speed motor related to the wipers by a system of connecting rods, often called the wiper arm (Fig. 1).

A wiper generally consists of an arm, pivoting at one end and with a long rubber blade attached to the other. The blade is swung back and forth over the windscreen, pushing water from its surface. The speed is normally adjustable, with several continuous speeds and often one or more intermittent settings. There are generally three speeds: fast, slow and intermittent, whose selection made by the driver.

It is often that the wiper system generates unwanted noise and vibration. Noise and vibration in the wiper system can be classified into three groups, namely, squeal noise, chattering and reversal noise. Squeal noise, sometimes called squeaky noise, is a high-frequency vibration of about 1000 Hz. Chattering or beep noise, is a low-frequency vibration of 100Hz or less. Reversal noise is an impact sound with a frequency of 500 Hz or less produced when the wiper reverses. These types of noise and vibration phenomenon lead to visual and audible annoyance for the driver and passengers [1].

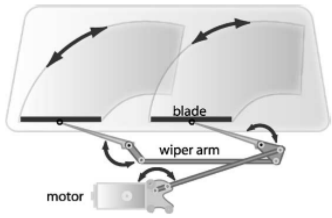


Fig. 1. Wiper system on a windscreen[2]

Numerous studies, using numerical and/or experimental approach, have been carried out to investigate noise and vibration of an automotive wiper system. They studied dynamic analysis of blade reversal behaviour using a 2-dimensional (2D) mechanical model of a wiper system and a spring-mass model of an arm and blade [3]. Extended studies considering a complete 3D model were also performed. Comparison between 2D and 3D model for the arm and blade was made and the result suggested that the 3D model could simulate the reversal behaviour of the wiper system more accurately than 2D model [4].

The investigation of squeal noise reduction using a mathematical model has been proposed [1, 5]. From the proposed model, material physical properties and design of the blade were varied. Experiments on squeal noise were also carried out to verify the effectiveness of the proposed material and design changes. A combined approach to study chatter vibrations for a wiper system has been performed [6]. Wiper motion tests were carried out on a developed test rig. Different attack angles and pressure were used and their effect on the wiper motion was observed. The study also developed a 2D mathematical model to demonstrate the influence of the geometrical configuration of the wiper system on the generation of unstable motion.

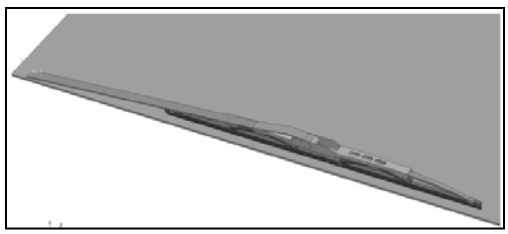
The employing of dither control to stabilize squeal noise in the wiper system also has been studied [7]. A FE model was developed in order to support the optimization of the control configuration. The study showed that with a proposed dither control, wiper squeal noise was effectively suppressed. The developing of a FE model to study dynamic instability of a flexible wiper system also has been developed [8]. The FE model was validated by experimental tests with different value of arm forces and attack angles of a rubber blade. The results of the study show that the predicted instabilities were close to those obtained in the experiments.

From the previous study, none of existing works studied noise and vibration of an automotive wiper using FE method particularly through complex eigenvalue analysis. This paper presents numerical studies on noise and vibration of an automotive wiper blade. A 3-dimensional finite element model of a wiper blade assembly is developed and then validated at the component level using modal analysis. Complex eigenvalue analysis available in ABAQUS is employed to determine the stability of the wiper blade assembly.

2. Development of Wiper Model

A detailed 3-dimensional FE model of a Proton windscreen wiper assembly is developed using Solidworks modeling software. Fig. 2(a) and 2(b) show a real wiper design and its FE model respectively. The FE model consists of a windscreen, a rubber blade, primary yoke and a wiper arm as shown in Fig.3. The windscreen is simplified as a flat surface in the FE model in order to avoid convergence issue. The assumption of flat surface is made based on the previous studies [6, 9].

(a)



(b)

Fig. 2. Windscreen wiper; (a) an actual wiper (b) FE model

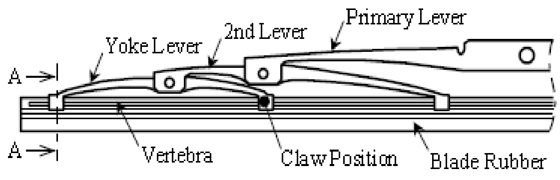


Fig. 3. Structure of wiper blade[3]

2.1 Validation of FE model

An experimental modal analysis (EMA) was performed on the individual wiper components in order to determine their normal mode response [10]. The EMA was performed at free-free boundary condition for the rubber blade, primary lever and yoke and secondary lever, whilst at fixed boundary condition for the windscreen.

The impact hammer test method is used to obtain natural frequencies of those components (Table 1). In doing so, a Kistler type 9722A500 impact hammer is used to produce the excitation force while a Kistler Type 8636C50 uni-axial accelerometer is fix-mounted onto the tested components [11]. The results showed very good correlation between predicted and measured natural frequencies for all wiper components. This is obtained by tuning Young's modulus and the density value of the wiper components. The updated material data of the wiper components are given in Table 2.

Table 1. Correlation of experimental modal analysis with FE analysis

Component	Mode No	Experimental Frequencies (Hz)	FE Analysis (Hz)
Windscreen	1	219	207
	2	242	248
	3	308	319
Rubber blade	1	61	42
	2	153	152
	3	286	281
Primary lever	1	247	247
Levers (second and yoke lever)	1	723	705
	2	835	857

Table 2. Material properties of wiper components

Component	Density (kg/m^3)	Young's Modulus (GPa)	Poisson's Ratio
Windscreen	2500	8.7	0.25
Rubber blade	1000	7.1e-3	0.49
Primary lever	7981	242.8	0.29
Levers	7981	464	0.29

2.2 Assembly Model of Wiper Components

The next stage is to bring all components together to form an assembly model. A combination of tie element and self-contact/surface to surface contact element are used to represent contact interaction between wiper components and windscreen/rubber blade interface respectively. Table 3 shows details of windscreen wiper couplings that are employed in the FE model assembly.

Table 3. Windscreen wiper model couplings

No.	Connections	Type of connection
1	Windscreen-Rubber blade	Surface to surface
2	Neck-shoulder	Self contact
3	Rubber blade-Yoke lever	Tie
4	Yoke lever-Second lever	Tie
5	Second lever-Primary yoke lever	Tie
6	Primary yoke lever-Wiper arm	Rigid body

3. Experiment of Noise and Vibration on Wiper

The measurement set-up is shown in Fig. 4, where a Kistler Type 8794A500 tri-axial accelerometer is attached to the primary yoke. The wiper used in the experiments is of the uni-blade type that typically found in the PROTON cars. Noise and vibration measurements of the wiper were carried out at wet environmental conditions and were measured at two different average speeds of 1.8 and 2.5 rad/s [12].

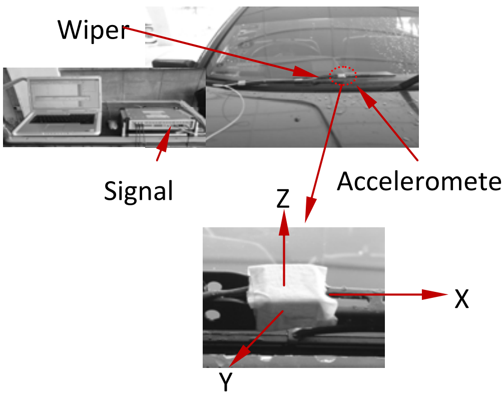
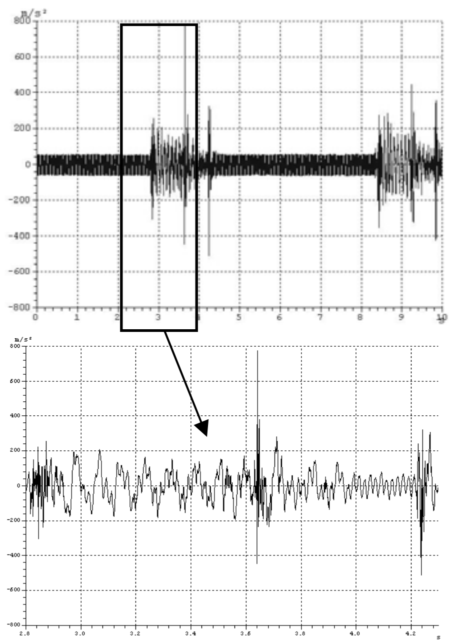
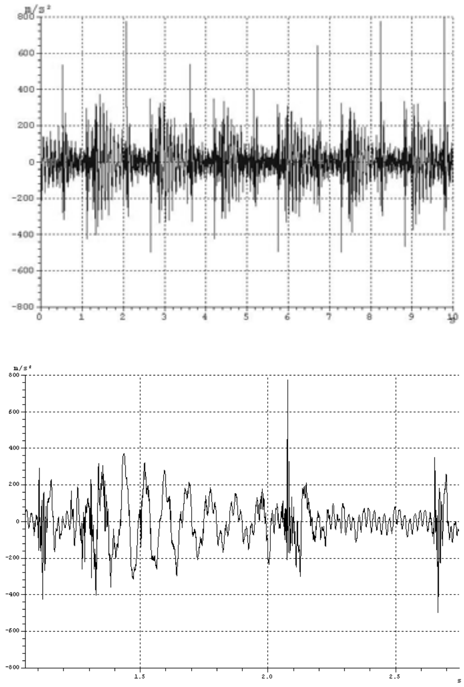


Fig. 4. Setup for noise and vibration measurement

For a rotational speed of 1.8 rad/s, acceleration response is shown in Fig. 5(a). It is seen that high vibration amplitude occurred rightly at the beginning and end of the wiper stroke. This may due to two reasons: stick-slip and/or negative velocity-friction characteristic mechanisms [6]. There is less idle time after one complete stroke for rotational speeds of 2.5 rad/s (Fig. 5(b)), compared to 4s idle time for rotational speed of 1.8 rad/s.



(a) Average speed of 1.8 rad/s at Z direction



(b) Average speed of 2.5 rad/s at Z direction

Fig. 5. Acceleration responses during wet condition

The above study suggests that the results are concurred with the findings of Goto et.al [1], where the study stated that noise could easily be generated before and after wiper stroke as shown in Fig. 6.

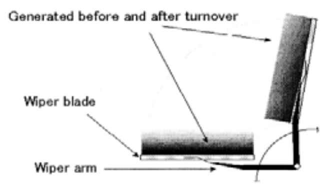
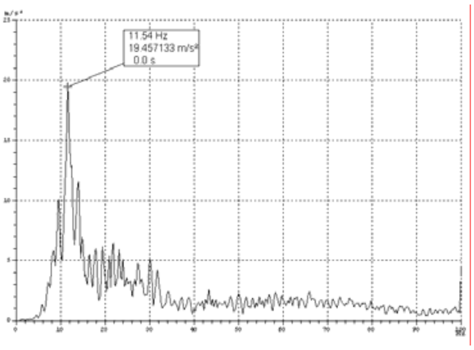
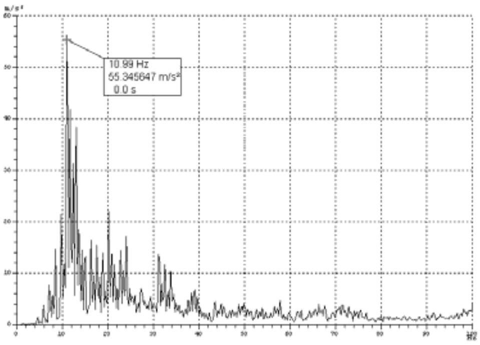


Fig. 6. Location of noise generation [1]

From acceleration responses in Fig. 7(a), it is found that at the speed of 1.8 rad/s, the noise is dominated at frequency around 12 Hz. For speed at 2.5 rad/s as depicted in Fig. 7(b) noise is generated at dominant frequency of 11 Hz. This has similar trend with previous speed. It seems that the noise frequency of the wiper is almost identical. From those measured frequencies, it can be said that current wiper system is experiencing chatter noise.

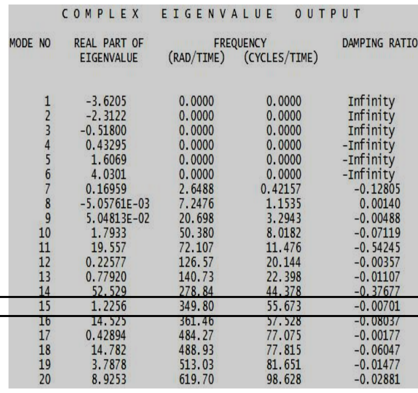


(a) Average speed of 1.8 rad/s



(b) Average speed of 2.5 rad/s

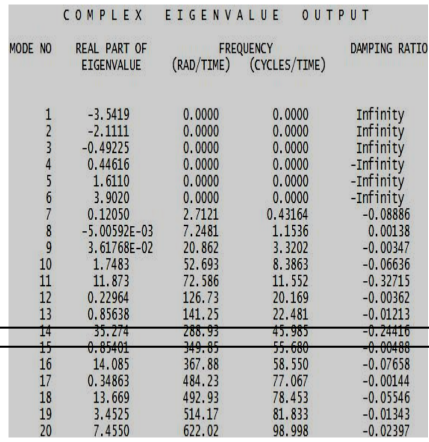
Fig. 7. Noise frequencies measured from the rubber Blade



COMPLEX EIGENVALUE OUTPUT

MODE NO	REAL PART OF EIGENVALUE	FREQUENCY (RAD/TIME)	FREQUENCY (CYCLES/TIME)	DAMPING RATIO
1	-3.6205	0.0000	0.0000	Infinity
2	-2.3122	0.0000	0.0000	Infinity
3	-0.51800	0.0000	0.0000	Infinity
4	0.43295	0.0000	0.0000	-Infinity
5	1.6069	0.0000	0.0000	-Infinity
6	4.0301	0.0000	0.0000	-Infinity
7	0.16959	2.6488	0.42157	-0.12805
8	-5.05761E-03	7.2476	1.1535	0.00140
9	5.04813E-02	20.698	3.2943	-0.00488
10	1.7933	50.380	8.0182	-0.07119
11	19.557	72.107	11.476	-0.54245
12	0.22577	126.57	20.144	-0.00357
13	0.77920	140.73	22.398	-0.01107
14	52.529	278.84	44.378	-0.37677
15	1.2256	349.80	55.673	-0.00701
16	14.525	361.46	57.528	-0.08037
17	0.42894	484.27	77.075	-0.00177
18	14.782	488.93	77.815	-0.06047
19	3.7878	513.03	81.651	-0.01477
20	8.9253	619.70	98.628	-0.02881

(a) Average speed of 1.8 rad/s



COMPLEX EIGENVALUE OUTPUT

MODE NO	REAL PART OF EIGENVALUE	FREQUENCY (RAD/TIME)	FREQUENCY (CYCLES/TIME)	DAMPING RATIO
1	-3.5419	0.0000	0.0000	Infinity
2	-2.1111	0.0000	0.0000	Infinity
3	-0.49225	0.0000	0.0000	Infinity
4	0.44616	0.0000	0.0000	-Infinity
5	1.6110	0.0000	0.0000	-Infinity
6	3.9020	0.0000	0.0000	-Infinity
7	0.12050	2.7121	0.43164	-0.08886
8	-5.00592E-03	7.2481	1.1536	0.00138
9	3.61768E-02	20.862	3.3202	-0.00347
10	1.7483	52.693	8.3863	-0.06636
11	11.873	72.586	11.552	-0.32715
12	0.22964	126.73	20.169	-0.00362
13	0.85638	141.25	22.481	-0.01213
14	35.274	288.93	45.985	-0.24416
15	0.85401	349.85	55.680	-0.00488
16	14.085	367.88	58.550	-0.07658
17	0.34863	484.23	77.067	-0.00144
18	13.669	492.93	78.453	-0.05546
19	3.4525	514.17	81.833	-0.01343
20	7.4550	622.02	98.998	-0.02397

(b) Average speed of 2.5 rad/s

Fig. 8. Results of complex eigenvalue analysis

4. Complex Eigenvalue Analysis

This section focuses on prediction of unstable analysis and describes wiper vibration characteristic at a system level. A preferred, complex eigenvalue analysis method is used to predict the unstable frequency. The complex eigenvalue are solved using the subspace projection that is available in ABAQUS.

In order to perform the complex eigenvalue analysis using ABAQUS, four main steps are required [12].

4.1 Simulation Result

Complex eigenvalue analysis defines instability of the system by positive real parts. Fig. 8 presents the results obtained from complex eigenvalue analysis. It is found that the frequencies in two different speeds are almost identical. This suggests that the rotational speed of the wiper may not influence the noise generated in the wiper system.

It is also found that the predicted results are reasonably close to those generated in the experiment as listed in Table 4.

Table 4. Comparison of FE and experimental results

Speeds (rad/s)	Experimental Frequency(Hz)	FE analysis (Hz)
1.8	11.5	11.5
2.5	10.9	11.6

4.2 Attack Angle (Deformation of Rubber Blade)

From the FE analysis, the attack angle for the rubber blade can be measured. The attack angle is the angle between the plane of the blade holder and a vector normal to the glass surface [9] as shown in Fig. 9.

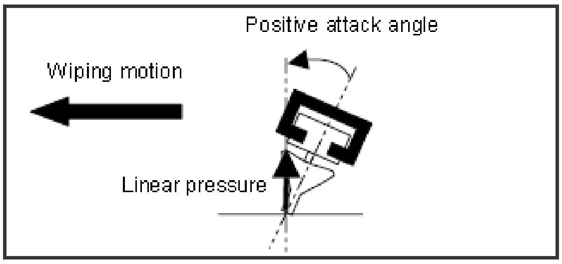


Fig. 9. Definition of attack angle [9]

It is found that, attack angle which is for the two different speeds are almost identical, i.e., about 16°. The deformed rubber blade in ABAQUS is shown in Fig. 10.

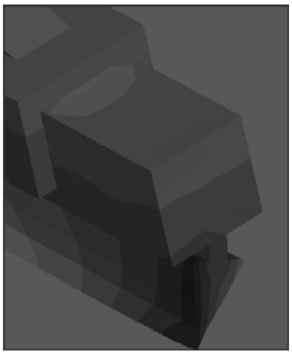


Fig. 10. Deformation of Rubber Blade

5. Conclusion

The wiper produces a low frequency vibration and noise called chatter, at dominant frequency of 11 Hz. It is found that, at different wiper average speeds, the chattering noise is generated before and after the wiper turnover. The complex eigenvalue analysis has been utilized in a finite element analysis to study low frequency squeal vibration problem. The measured chatter noise has been successfully replicated in the analysis. It has been shown in this paper as well as in the literature that the complex eigenvalue analysis is useful tool for low frequency noise analysis. The approach could generate almost identical chatter frequency.

It is the authors' intention to make further investigation to improve noise and vibration of the wiper system by proposing several structural modifications to rubber blade in subsequent work.

Acknowledgements

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References

1. S. Goto, H. Takashi, T. Oya, Clarification of Mechanism of Wiper Blade Rubber Squeal Noise Generation, JSAE Review 22 (2001), 57-62.
2. J. Lévine, On the Synchronization of a Pair of Independent Windshield Wipers, IEEE Transactions on Control Systems Technology, Vol. 12 No. 5 (2004).
3. S. Okura, T. Sekiguchi, T. Oya, Dynamic Analysis of Blade Reversal Behavior in a Windshield Wiper System, SAE Technical Paper, 2000-01-0127.
4. S. Okura, T. Oya, Complete 3D Dynamic Analysis of Blade Reversal Behavior in a Windshield Wiper System, SAE Technical Paper, 2003-01-1373.
5. S. Goto, H. Takahashi, T. Oya, Investigation of Wiper Blade Noise Reduction Measures, SAE Technical Paper, 2001-01-1410.
6. R. Grenouillat, C. Leblanc, Simulation of Mechanical Pressure in a Rubber-Glass Contact for Wiper Systems, SAE Technical Paper, 2002-01-0798.
7. B. Stallaert, F. Doucet, J. Rys, A. Diallo, S. Chaigne, J. Swevers, P. Sas, Application of Dither Control for Automotive Wiper Squeal, Proceedings of ISMA (2006), 263-272.
8. C.R. Chevennement, T. Dreher, P. Alliot, E. Aubry, J.P. Lainé, L. Jézéquel, Flexible Wiper System Dynamic Instabilities: Modelling and Experimental Validation, Experimental Mechanics, 47 (2007), 201–210.
9. R. Grenouillat, C. Leblanc, Simulation of Chatter Vibrations for Wiper Systems, SAE Technical Paper, 2002-01-1239.
10. D.J. Ewins, Modal Testing: Theory and Practice, Research Studies Press, Letchworth, 1984.
11. A.R. Abu Bakar, E. Jamaludin, C.Y. Leong, An Experimental Investigation into Noise and Vibration of an Automotive Wiper, Proceedings of the regional Conferences on Advance in Noise, Vibration and Comfort (2007), 261-269.
12. H. Idris, Study of Windshield Wiper Noise, Bachelor Engineering Project Universiti Teknologi Malaysia (2007).
13. A.R. Abu Bakar, A. Sharif, M.Z.A Rashid, H. Ouyang, Brake Squeal: Complex Eigenvalue versus Dynamic Transient Analysis, SAE Technical Paper, 2007-01-3954.

CHAPTER 4

FINITE ELEMENT ANALYSIS OF WINDSCREEN WIPER CHATTER NOISE AND ITS SUPPRESSION APPROACH THROUGH STRUCTURAL MODIFICATIONS

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(Paper presented at International Conference on Advances in Mechanical Engineering 2009)

Abstract

This paper presents an approach to predict automotive windscreen wiper chatter noise using finite element method. In this study, a 3-dimensional finite element model of a real wiper blade is developed and then validated using experimental modal analysis. In order to assess stability of the wiper blade assembly, complex eigenvalue analysis that made available in ABAQUS is performed. The positive real parts of complex eigenvalue indicate unstable system. The baseline model is first simulated and stability of the system is examined. Having found a predicted unstable frequency which is chatter noise, various structural modifications are proposed in order to reduce it.

Keywords: *wiper; chatter; finite element; complex eigenvalue; structural modifications; modal analysis*

1. Introduction

Windscreen wipers are indispensable components to the maintenance of a safe and comfortable field of vision when driving on rainy days. Today, almost all automobile are equipped with windscreen wiper, often by legal requirement. Clear vision for the car driver is an important prerequisite for safety in road traffic. A conventional wiper as shown in Figure 1 generally consists of an arm, pivoting at one end and with a long rubber blade attached to the other [1]. The blade is swung back and forth over the windscreen, pushing water from its surface. The mechanical structure of the wiper blades is attached to the arm tips, holds the rubber blade, which drains the water off the windscreen or to smooth the water on the surface of the windscreen in order to create a thin film that allows light to pass through it without refracting or bending as shown in Figure 2.

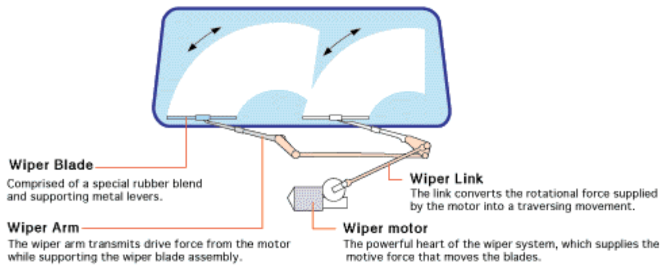


Figure1: Wiper system on a windscreen [1]

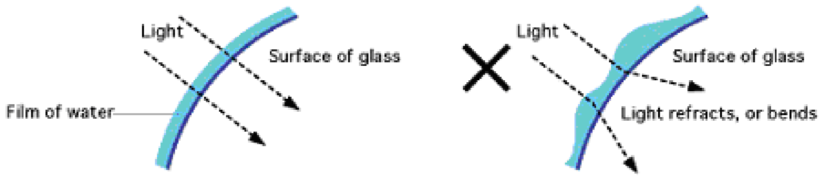


Figure 2: Load distribution of a wiper blade [1]

It is very often that the windscreen wiper generates unwanted noise and vibration. This noise and vibration can be classified into three categories namely, squeal noise, chattering and reversal noise. Squeal noise, sometimes called squeaky noise, is a high-frequency vibration of about 1000 Hz. Chattering or beep noise, is a low-frequency vibration of 100Hz or less. Reversal noise is an impact sound with a frequency of 500 Hz or less produced when the wiper reverses. These types of noise and vibration lead to visual and audible annoyance for the driver and passengers [2].

Numerous studies using analytical, numerical and experimental approaches have been carried out to investigate noise and vibration of an automotive wiper system. Okura et al [3] performed dynamic analysis of blade reversal behaviour using a 2-dimensional (2D) mechanical model of a wiper system and a spring-mass model of an arm and blade. They, in another work, further studied the dynamic analysis using a complete 3-dimensional (3D) model. Comparison between the 2- and 3- dimensional model for the arm and blade was made and the results suggested the 3D model could simulate the reversal behaviour of the wiper system more accurately than the 2D model [4].

The squeal noise reduction using a mathematical model has been proposed in [2, 5]. In their studies, physical properties and design of the blade were varied. In order to compliment the predicted results, experiments on squeal noise were also carried out to verify the effectiveness of the proposed material and design changes. A combined approach to study chatter vibrations for a wiper system has also been performed in [6]. Wiper motion tests were carried out on a developed test rig. Different attack angles and pressure were used and their effect on the wiper motion was observed. They also developed a 2D mathematical model to demonstrate the influence of the geometrical configuration of the wiper system on the generation of unstable motion. The application of dither control to stabilize squeal noise in the wiper system has been introduced in [7]. A finite element (FE) model was developed in order to support the optimization of the control configuration. The study showed that with a proposed dither control, wiper squeal noise was effectively suppressed. Chevennement et al [8] developed a FE model to study dynamic instability of a flexible wiper system. Different values of arm forces and attack angles of a rubber blade were selected and simulated to examine their effects on the vibration response of the wiper. The predicted results were close to those obtained in the experiments.

From the aforementioned studies, it is found that none of them investigates wiper vibration using FE method through complex eigenvalue analysis. This paper presents an approach to predict automotive windscreen wiper vibration using finite element method. In this study, a 3-dimensional finite element model of a real wiper blade is developed and then validated using experimental modal analysis. In order to assess stability of the wiper blade assembly, complex eigenvalue analysis that made available in ABAQUS is performed. The positive real parts of complex eigenvalue indicate unstable system. The baseline model is first simulated and stability of the system is examined. Having found unstable frequency which is the chatter noise, various structural modifications are proposed in order to reduce it.

2. Experimental approaches

This section describes in details experimental approaches to study vibration of the windscreen wiper. The first experimental approach is using experimental modal analysis to validate the developed 3 dimensional FE model in terms of natural frequency and its associated mode shape. The second experiment is carried out to study vibration of the wiper in the wet condition.

2.1 Experimental Modal Analysis (EMA)

EMA is performed on the individual wiper components in order to determine its dynamic characteristics [9]. The EMA is performed at free-free boundary condition for the rubber blade, primary lever and yoke and secondary lever, whilst at fixed boundary condition for the windscreen. The impact hammer test method is used to obtain natural frequencies of those components. In doing so, a Kistler type 9722A500 impact hammer is used to produce the excitation force while a Kistler Type 8636C50 uni-axial accelerometer is fix-mounted onto the tested components [10] as shown in Figure 3.

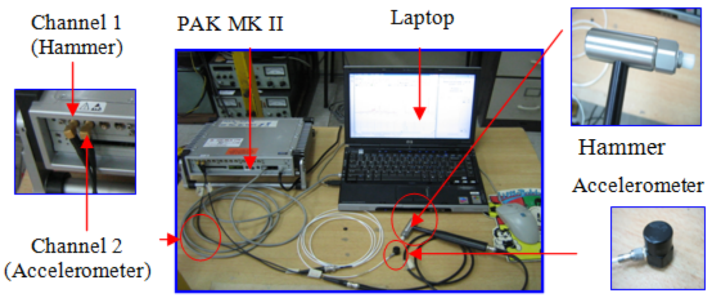


Figure 3: Experimental setup for modal testing

2.2 Experiment of Noise and Vibration on Wiper

The measurement set-up is shown in Figure 4, where a Kistler Type 8794A500 tri-axial accelerometer is attached to the primary yoke. The wiper used in the experiments is of the uni-blade type that typically found in the national cars. Vibration measurement of the wiper is carried out in wet environmental condition and is measured at two different wiper average speeds of 1.8 and 2.5 rad/s [11].

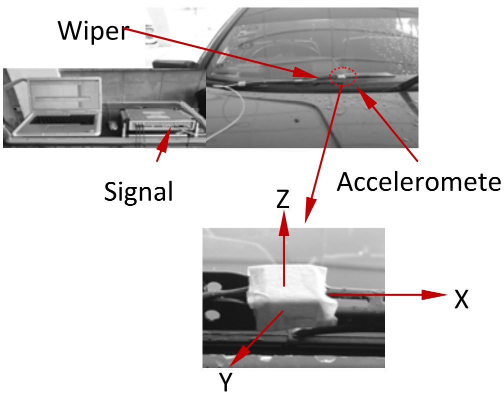


Figure 4: Setup for noise and vibration measurement

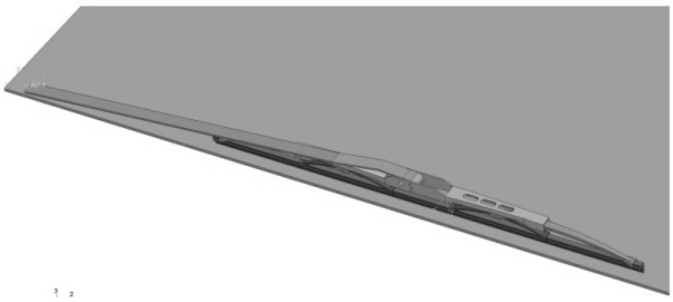
3. Development of a Finite Element (FE) Model

In this section, development and validation process of a wiper blade model is described. In the validation process, predicted natural frequencies and mode shapes will be compared to those found in the experiment.

3.1 Modeling of a Wiper Blade

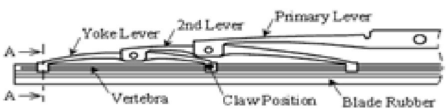
A detailed 3dimensonal FE model of a passenger car windscreen wiper assembly is developed as shown in Figure 5. The FE model consists of a windscreen, a rubber blade, primary yoke and a wiper arm as shown in Figure 6. The windscreen is simplified as a flat surface in the FE model in order to reduce computational time. The assumption of a flat surface is made based on the previous studies [6]. The windscreen and vertebrata are developed using 8-node (C3D8) linear solid elements while the rubber blade are developed using combination of 4-node (C3D4) and 8-node (C3D8) linear solid elements. The levers (primary, second and third) are developed using 4-node (C3D4) linear solid element while the wiper arm are developed using combination of 4-node (C3D4), 6-node (C3D6) and 8-node (C3D8) linear solid elements. Element types in brackets show the notation in ABAQUS nomenclature. Details for each of the components are given in Table 1.

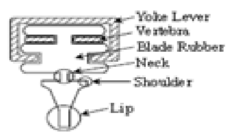
(a)



(b)

Figure 5: Windscreen wiper; (a) an actual wiper (b) FE model

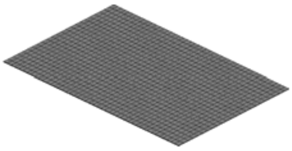
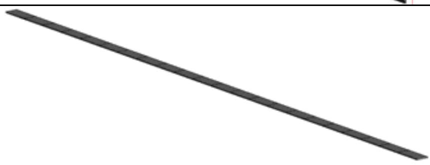




(a)Structure of wiper blade (b) Cross-section A-A Figure

Figure 6: Details of wiper blade [4]

Table 1: Description of wiper blade components

Components		Types of element	No. of element	No. of nodes
	Windscreen	C3D8	1035	2208
	Rubber blade	C3D4 C3D8	75446	30802
	Vertebrata	C3D8	22	92
	Third levers (both side)	C3D4	13721	5025
	Second levers (both side)	C3D4	3388	1415
	Primary lever	C3D4	5712	2256
	Wiper arm	C3D8 C3D6 C3D4	4198	4930

The next development stage is to bring all components together to form an assembly model. A combination of tie element and self-contact/surface to surface contact element are used to represent contact interaction between wiper components and windscreen/rubber blade interface respectively. Table 2 shows details of windscreen wiper couplings that are used in the FE assembly model. Surface-to-surface contact interaction is used between windscreen and rubber blade in order to capture a realistic contact pressure distribution which is essential in the complex eigenvalue analysis. The neck and shoulder can deform largely due to force exerts on it and they may contact each other. Hence, self contact interaction is a suitable option to represent contact between the two geometries. Tie element is used to couple together between rubber blade and third lever, and third lever and second lever. For the third lever and second lever, the tie element is freely to rotate in its axial direction and it behaves like a hinge.

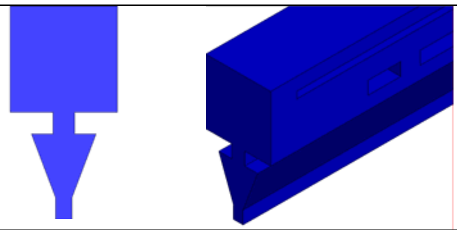
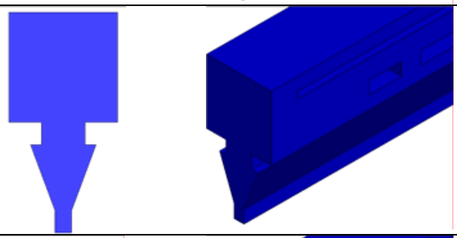
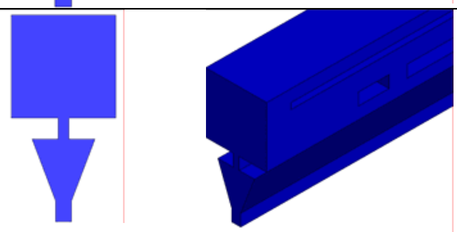
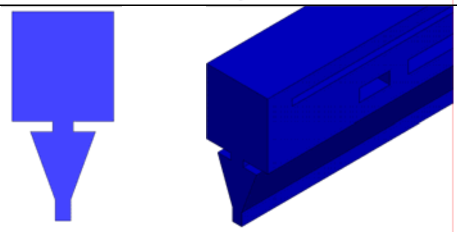
Table 2: Windscreen wiper model couplings

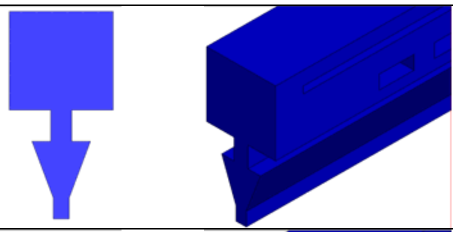
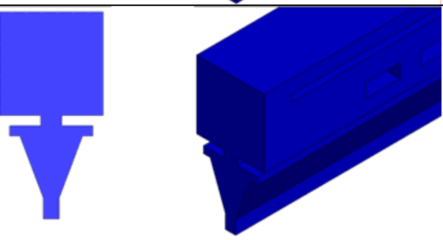
No.	Connections	Type of connection
1	Windscreen-rubber blade	Surface to surface
2	Neck-shoulder	Self contact
3	Rubber blade-third lever	Tie
4	Third lever-Second lever	Tie
5	Second lever-Primary lever	Tie
6	Primary lever-Wiper arm	Rigid body

3.2 Structural Modifications

In this section, various structural modifications are proposed in order to reduce chatter vibration of the wiper blade assembly. This can be achieved when the positive real parts of the complex eigenvalue of the baseline model are being reduced or eliminated. In this study, only rubber blade part is modified. There are five modifications of a new blade model (NBM) design are proposed to suppress the chatter generated in the wiper system. Details of the structural modification are given in Table 3.

Table 3: Proposed structural modifications

No.	Modification	Description
Baseline		Original wiper blade with a neck size 1mm width and 1mm height. It has no edge on both side of the blade shoulder.
NBM 1		The neck of the blade is thicker than the baseline design. The width is increased to 2mm.
NBM 2		The neck of the blade is thinner than the baseline design. The width is reduced to 0.5mm.
NBM 3		The height of the blade neck has been decreased from 1mm to 0.5mm.

NBM 4		The height of the blade neck has been increased from 1mm to 1.5mm.
NBM 5		An edge has been added in both side of the blade shoulder and the height of the neck has been decreased from 1mm to 0.5mm.

4. Results and Discussion

The results obtained from the experimental and FE method is utilized for comparison and validation. The first section presents the correlation between EMA and FE modal analysis results. Then, vibration results from experiment will be discussed. Next, complex eigenvalue analysis of baseline model is performed for the validation with the experimental results. Finally, complex eigenvalue analysis is performed on the modified wipers. A good modification should not produce any positive real parts.

4.1 Validation of FE Model

Results in Table 4 show that there are very good correlation between predicted and measured data for all wiper components. The results are based on the material data given in Table 5.

Table 4: Correlation of experimental modal analysis with FE analysis

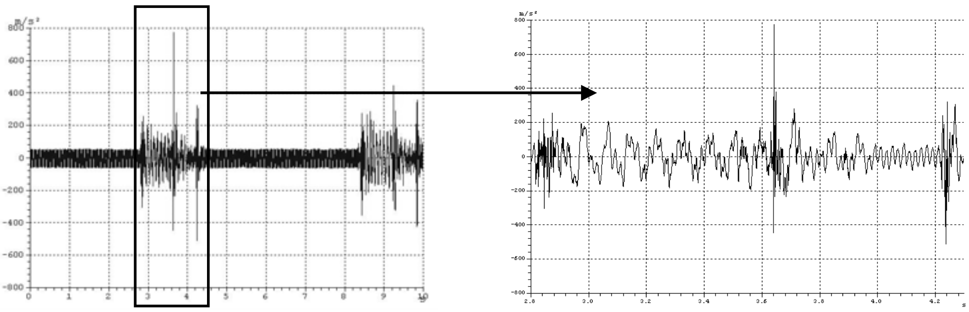
Component	Mode No.	Experimental Frequencies (Hz)	FE Analysis (Hz)
Windscreen	1	219	207
	2	242	248
	3	308	319
Rubber blade	1	61	42
	2	153	152
	3	286	281
Primary lever	1	247	247
Levers (second and yoke lever)	1	723	705
	2	835	857

Table 5: Material properties of wiper components

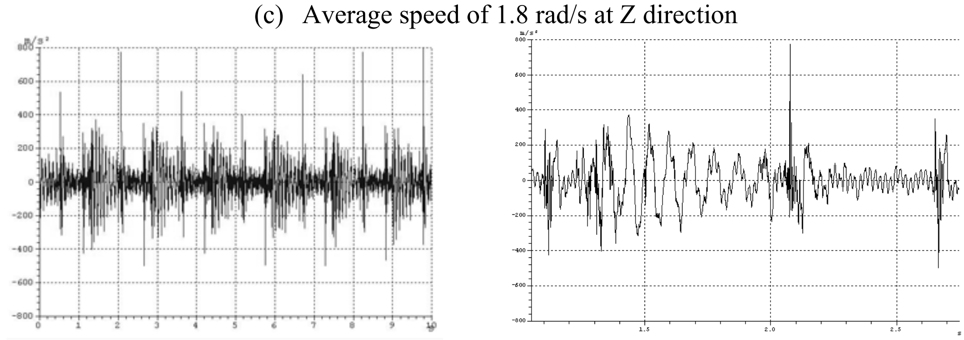
Component	Density (kg/m^3)	Young’s Modulus (GPa)	Poisson’s Ratio
Windscreen	2500	8.7	0.25
Rubber blade	1000	7.1e-3	0.49
Primary lever	7981	242.8	0.29
Levers	7981	464	0.29

4.2 Experiment of Noise and Vibration

For a wiper rotational speed of 1.8 rad/s, acceleration response is shown in Figure 7(a). It is seen that high vibration amplitude occurred rightly at the beginning and end of the wiper stroke. This may due to two reasons: stick-slip and/or negative velocity-friction characteristic mechanisms [6]. There is less idle time after one complete stroke for rotational speeds of 2.5 rad/s (Figure 7(b)), compared to 4s idle time for rotational speed of 1.8 rad/s. The results are seen comparable to the findings of Goto et.al [2], where the vibration could easily be generated before and after wiper stroke as shown in Figure 8.



(c) Average speed of 1.8 rad/s at Z direction



(d) Average speed of 2.5 rad/s at Z direction

Figure 7: Acceleration responses during wet condition

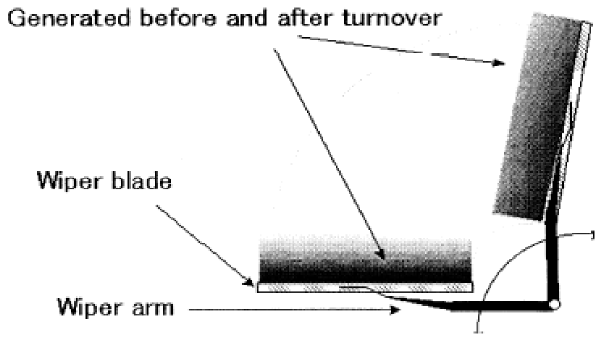
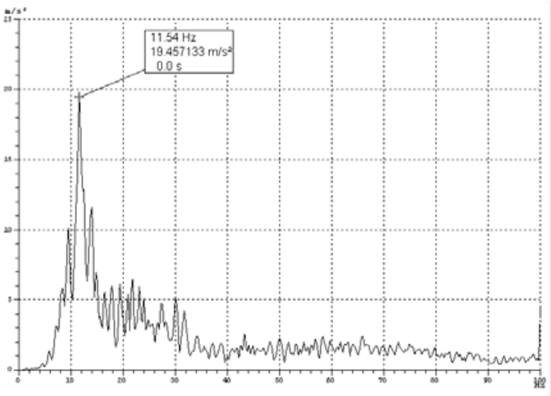
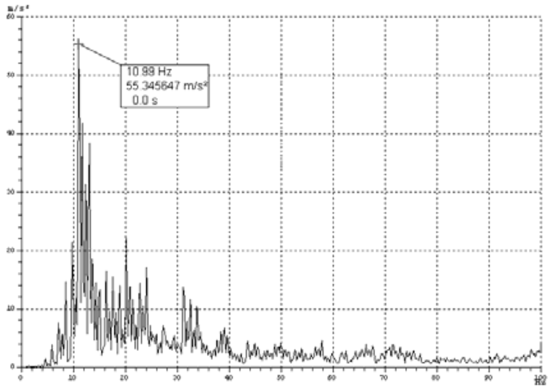


Figure 8: Location of noise generation [1]

From acceleration responses figure in Figure 9(a), it is found that at the wiper speed of 1.8 rad/s, the vibration is dominated at frequency around 12 Hz. For speed at 2.5 rad/s as depicted in Figure 9(b) vibration is generated at dominant frequency of 11 Hz. It seems that the vibration frequency of the wiper is almost the same for different speeds. From those measured frequencies, it can be said that current wiper system is experiencing chatter vibration.



(a) Average speed of 1.8 rad/s



(b) Average speed of 2.5 rad/s

Figure 9: Vibration frequencies measured from the rubber blade

4.3 Complex Eigenvalue Analysis

This section focuses on prediction of unstable frequency at a system level. Complex eigenvalue analysis can be a tool to trace the regions of the parameter space that lead to instability of the wiper blade system. For wiper chattering analysis, the most important source of nonlinearity is the frictional sliding contact between the windscreen and the blade. ABAQUS allows for a convenient, but general definition of contact interfaces by specifying the contact surface and the properties of the interfaces. ABAQUS has developed a new approach of complex eigenvalue analysis to simulate the disc brake squeal noise [12]. It is thought that this new approach can also be applied to study windscreen wiper chatter noise. It starts from preloading the blade pressure, rotating the wiper arm, and then extracting natural frequencies and complex eigenvalue, this new approach combines all steps in one seamless run. The complex eigenvalue problem is solved using the subspace projection method, thus a natural frequency extraction must be performed first in order to determine the projection subspace. The positive real parts of the complex eigenvalues indicate the degree of instability of the wiper assembly and are thought to indicate the likelihood of chatter occurrence. The essence of this method lies in the asymmetric stiffness matrix that is derived from the contact stiffness and the friction coefficient at the blade/windscreen interface. Details of the complex eigenvalue formulation can be found in [13].

4.3.1 Baseline Model

First, complex eigenvalue analysis is performed on the baseline model. The frequency of interest is ranging up to 500 Hz and at two different average rotational speeds of 1.8 rad/s and 2.5 rad/s. Figure 10 presents the results of unstable frequencies obtained from complex eigenvalue analysis for baseline model and the results from the experiment. From the analysis, it is found that there are eleven unstable frequencies predicted compared to one chattering frequency captured in the experiment. It is found that there are over-predictions in the simulation results even though one of the chatter frequencies is reasonably matched with the experimental data. From Figure 10, it is suggested that the different average speed of the wiper may not influence the vibration generated in the wiper system.

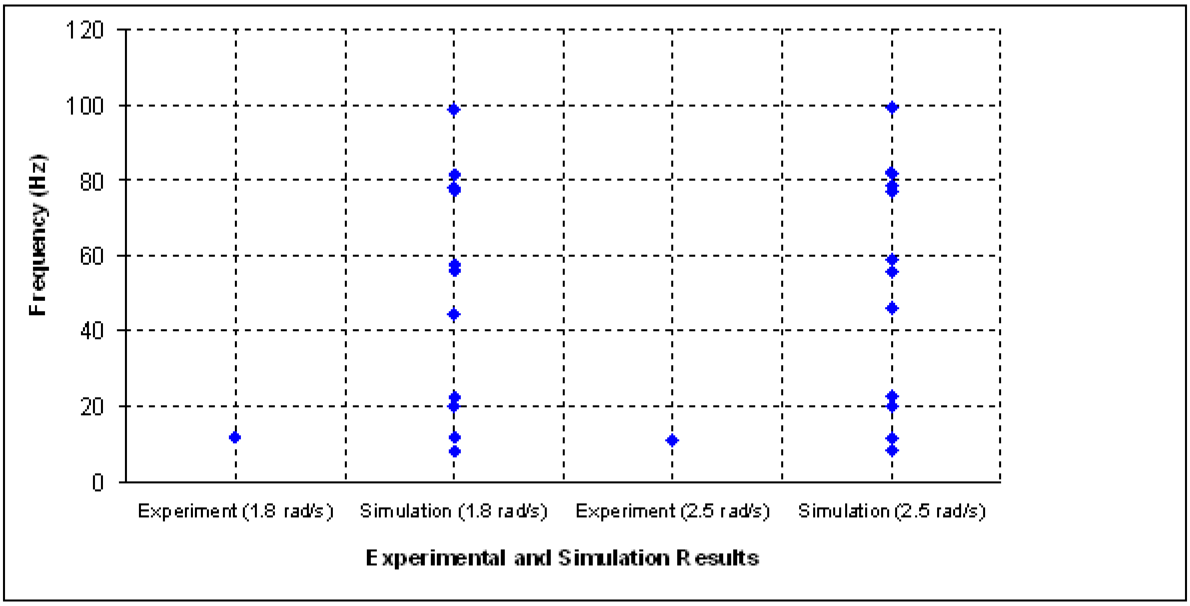


Figure 10: Predicted results for baseline model

4.3.2 Structural modifications

The predicted unstable frequencies for different blade modifications are shown in Figure 11. From the predicted results, only NBM 1 and NBM 4 can totally eliminate the chattering frequencies. There are seven unstable frequencies are generated in NBM 2 and NBM 3. The predicted unstable frequencies are 8Hz, 11Hz, 22Hz, 72Hz, 77Hz, 80Hz and 94Hz for NBM 2, and 12Hz, 21Hz, 25Hz, 58Hz, 74Hz, 78Hz and 82Hz for NBM 3. Although NBM 2 and NBM 3 have same total number of unstable frequencies prediction, the value of predicted unstable frequencies is different. For NBM 5, it has only one unstable frequency at 12Hz.

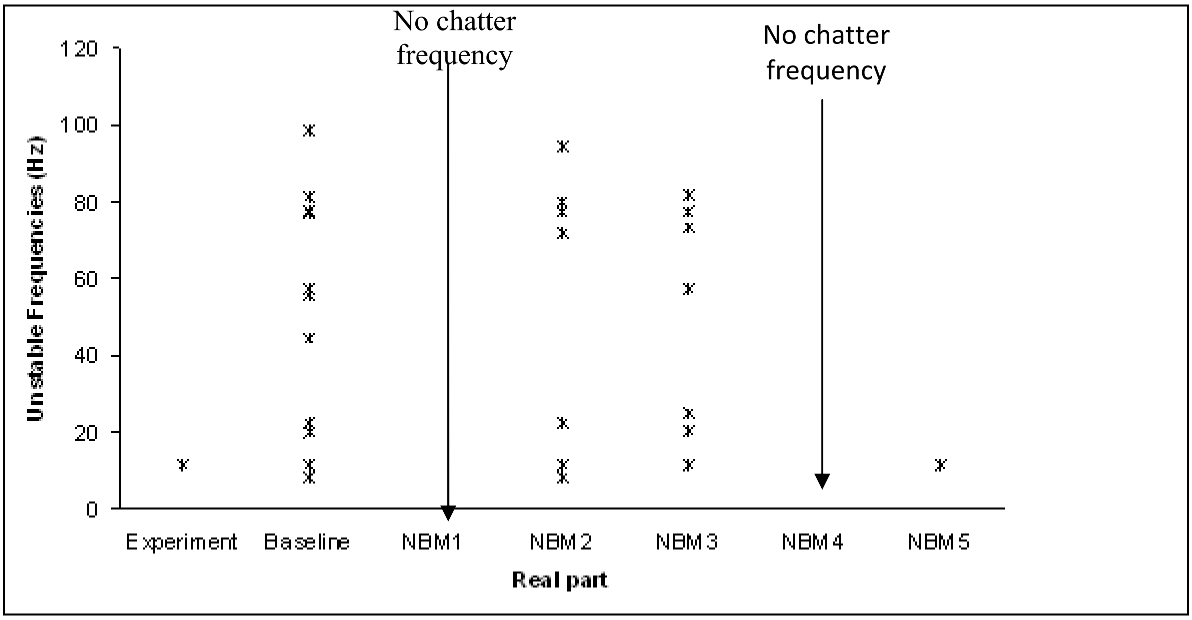


Figure 11: Predicted results for different structural modifications

Conclusion

This paper presents a numerical analysis to predict wiper blade chatter noise using FE method. Complex eigenvalue analysis that made available in commercial software package, ABAQUS is used to predict chatter frequencies. From the experiment, the result shows that the windscreen wiper produces a low frequency noise called chatter, at dominant frequency of 11Hz. It is found that, at different wiper average speeds, the chattering vibration is generated before and after the wiper turnover. The complex eigenvalue analysis has been utilized in a finite element analysis to study chatter problem. The measured chatter frequency has been successfully replicated in the analysis. Initially, there are eleven unstable frequencies (chatter) appeared in the baseline model. Based on the baseline results, various structural modifications have been proposed and simulated using complex eigenvalue analysis in order to suppress the chatter frequency. From the five proposed modifications, it is found that NBM 1 and NBM 3 can totally eliminate the positive real parts which indicate no chatter appears in wiper blade assembly. This indicates complex eigenvalue analysis can be used as a tool to predict vibration in the windscreen wiper.

Acknowledgements

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References

[1]Denso International Product Co., Wiper Technical Information, www.denso.sg/tpl/pdtlineup_wiper_technicalinfo.html (24 September 2008)
[2]S. Goto, H. Takashi, T. Oya, Clarification of Mechanism of Wiper Blade Rubber Squeal Noise Generation, JSAE Review 22, 57-62 (2001).
[3]S. Okura, T. Sekiguchi, T. Oya, Dynamic Analysis of Blade Reversal Behavior in a Windshield Wiper System, SAE Technical Paper, 2000-01-0127 (2000).
[4]S. Okura, T. Oya, Complete 3D Dynamic Analysis of Blade Reversal Behavior in a Windshield Wiper System, SAE Technical Paper, 2003-01-1373 (2003).

[5]S. Goto, H. Takahashi, T. Oya, Investigation of Wiper Blade Noise Reduction Measures, SAE Technical Paper, 2001-01-1410 (2001).
[6]R. Grenouillat, C. Leblanc, Simulation of Chatter Vibrations for Wiper Systems, SAE Technical Paper, 2002-01-1239 (2002).
[7]B. Stallaert, F. Doucet, J. Rys, A. Diallo, S. Chaigne, J. Swevers, P. Sas, Application of Dither Control for Automotive Wiper Squeal, Proceedings of ISMA, 263-272 (2006).
[8]C.R. Chevennement, T. Dreher, P. Alliot, E. Aubry, J.P. Lainé, L. Jézéquel, Flexible Wiper System Dynamic Instabilities: Modelling and Experimental Validation, Experimental Mechanics, 47, 201–210 (2007).
[9]D.J. Ewins, Modal Testing: Theory and Practice, Research Studies Press, Letchworth, (1984).
[10]A.R. Abu Bakar, E. Jamaludin, C.Y. Leong, An Experimental Investigation into Noise and Vibration of an Automotive Wiper, Proceedings of the Regional Conferences on Advance in Noise, Vibration and Comfort, 261-269 (2007).
[11]H. Idris, Study of Windshield Wiper Noise, BEng Thesis, Department of Automotive Engineering, Universiti Teknologi Malaysia (2007).
[12]ABAQUS Analysis User's Manual, Version 6.5 (2004).
[13]A.R. Abu Bakar and H. Ouyang, Complex Eigenvalue Analysis and Dynamic Transient Analysis in Predicting Disc Brake Squeal, Int. J. Vehicle and Vibration, 2(2), 143-155 (2006).

CHAPTER 5

Complex eigenvalue analysis of windscreen wiper chatter noise and its suppression through structural modifications

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ABSTRACT:

This paper presents an approach to predict automotive windscreen wiper chatter noise using finite element method. In this study, a 3-dimensional finite element model of a real wiper blade is developed and then validated using experimental modal analysis. In order to assess stability of the wiper blade assembly, complex eigenvalue analysis that made available in ABAQUS is performed. The positive real parts of complex eigenvalue indicate unstable system. The baseline model is first simulated and stability of the system is examined. Having found a predicted unstable frequency which is chatter noise, various structural modifications are proposed in order to reduce it.

KEYWORDS:

Wiper; chatter; finite element; complex eigenvalue; structural modifications; modal analysis

CITATION:

I.M. Awang, A.R. AbuBakar, B.A. Ghani, R.A. Rahman, and M.Z.M. Zain. 2009. Complex eigenvalue Analysis of Windscreen Wiper Chatter Noise and its Suppression by Structural Modifications, *Int. J. Vehicle Structures & Systems*,1(1-3), 24-29.

1. Introduction

Windscreen wipers are indispensable components to the maintenance of a safe and comfortable field of vision when driving on rainy days. Today, almost all automobile are equipped with windscreen wiper, often by legal requirement. Clear vision for the car driver is an important prerequisite for safety in road traffic. A conventional wiper as shown in Figure 1 generally consists of an arm, pivoting at one end and with a long rubber blade attached to the other [1]. The blade is swung back and forth over the windscreen, pushing water from its surface. The mechanical structure of the wiper blades is attached to the arm tips, holds the rubber blade, which drains the water off the windscreen or to smooth the water on the surface of the windscreen in order to create a thin film that allows light to pass through it without refracting or bending as shown in Figure 2.

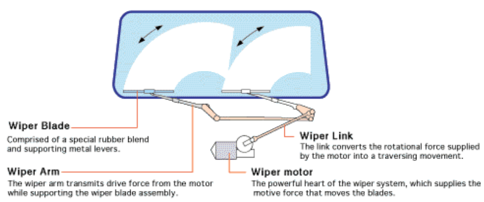

Figure 1: Wiper system on a windscreen [1]

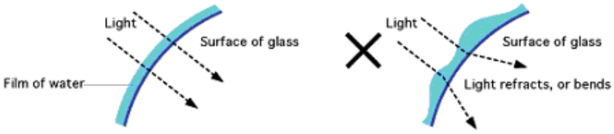

Figure 2: Load distribution of a wiper blade [1]

It is very often that the windscreen wiper generates unwanted noise and vibration. This noise and vibration can be classified into three categories namely, squeal noise, chattering and reversal noise. Squeal noise, sometimes called squeaky noise, is a high-frequency vibration of about 1000 Hz. Chattering or beep noise, is a low-frequency vibration of 100Hz or less. Reversal noise is an impact sound with a frequency of 500 Hz or less produced when the wiper reverses. These types of noise and vibration lead to visual and audible annoyance for the driver and passengers [2].

Numerous studies using analytical, numerical and experimental approaches have been carried out to investigate noise and vibration of an automotive wiper system. Okura et al [3] performed dynamic analysis of blade reversal behaviour using a 2-dimensional (2D) mechanical model of a wiper system and a spring-mass model of an arm and blade. They, in another work, further studied the dynamic analysis using a complete 3-dimensional (3D) model. Comparison between the 2- and 3-dimensional model for the arm and blade was made and the results suggested the 3D model could simulate the reversal behaviour of the wiper system more accurately than the 2D model [4].

The squeal noise reduction using a mathematical model has been proposed in [2, 5]. In their studies, physical properties and design of the blade were varied. In order to compliment the predicted results, experiments on squeal noise were also carried out to verify the effectiveness of the proposed material and design changes. A combined approach to study chatter vibrations for a wiper system has also been performed in [6]. Wiper motion tests were carried out on a developed test rig. Different attack angles and pressure were used and their effect on the wiper motion was observed. They also developed a 2D mathematical model to demonstrate the influence of the geometrical configuration of the wiper system on the generation of unstable motion. The application of dither control to stabilize squeal noise in the wiper system has been introduced in [7]. A finite element (FE) model was developed in order to support the optimization of the control configuration. The study showed that with a proposed dither control, wiper squeal noise was effectively suppressed. Chevennement et al [8] developed a FE model to study dynamic instability of a flexible wiper system. Different values of arm forces and attack angles of a rubber blade were selected and simulated to examine their effects on the vibration response of the wiper. The predicted results were close to those obtained in the experiments.

From the aforementioned studies, it is found that none of them investigates wiper vibration using FE method through complex eigenvalue analysis. This paper presents an approach to predict automotive windscreen wiper vibration using finite element method in general and complex eigenvalue analysis in particular. In this study, a 3-dimensional finite element model of a real wiper blade is developed and then validated using experimental modal analysis. In order to assess stability of the wiper blade assembly, complex eigenvalue analysis that made available in ABAQUS is performed. The positive real parts of complex eigenvalue indicate unstable system. The baseline model is first simulated and stability of the system is examined. Having found unstable frequency which is the chatter noise, various structural modifications are proposed in order to reduce it.

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This section describes in details experimental approaches to study vibration of the windscreen wiper. The first experimental approach is using experimental modal analysis to validate the developed 3 dimensional FE model in terms of natural frequency and its associated mode shape. The second experiment is carried out to study vibration of the wiper in the wet condition.

2.1 Experimental Modal Analysis (EMA)

EMA is performed on the individual wiper components in order to determine its dynamic characteristics [9]. The EMA is performed at free-free boundary condition for the rubber blade, primary lever and yoke and secondary lever, whilst at fixed boundary condition for the windscreen. The impact hammer test method is used to obtain natural frequencies of those components. In doing so, a Kistler type 9722A500 impact hammer is used to produce the excitation force while a Kistler Type 8636C50 uni-axial accelerometer is fix-mounted onto the tested components [10] as shown in Figure 3.

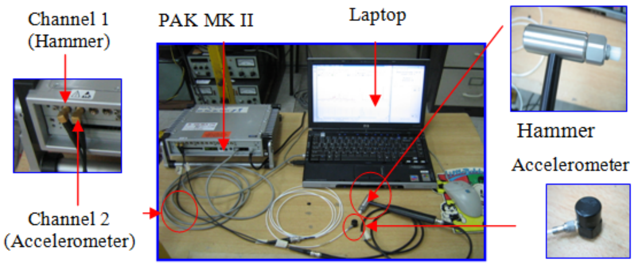


Figure 3: Experimental setup for modal testing

2.2 Experiment of noise and vibration on wiper

The measurement set-up is shown in Figure 4, where a Kistler Type 8794A500 tri-axial accelerometer is attached to the primary yoke. The wiper used in the experiments is of the uni-blade type that typically found in the national cars. Vibration measurement of the wiper is carried out in wet environmental condition and is measured at two different wiper average speeds of 1.8 and 2.5 rad/s [11].

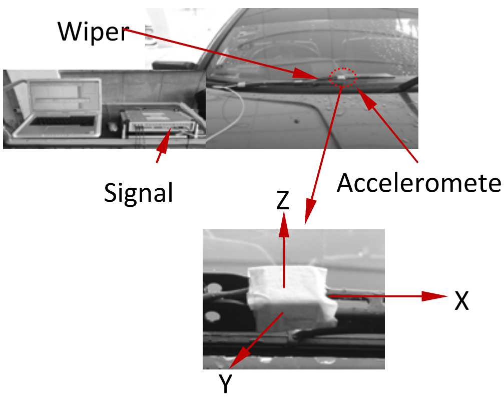


Figure 4: Setup for vibration measurement

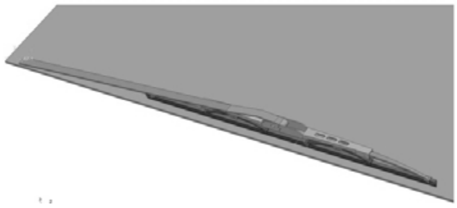
3. Development of a Finite Element (FE) Model

In this section, development and validation process of a wiper blade model is described. In the validation process, predicted natural frequencies and mode shapes will be compared to those found in the experiment.

3.1 Modeling of a Wiper Blade

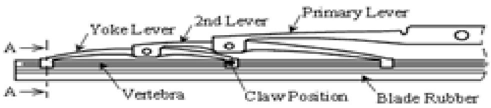
A detailed 3dimensonal FE model of a passenger car windscreen wiper assembly is developed as shown in Figure 5. The FE model consists of a windscreen, a rubber blade, primary yoke and a wiper arm as shown in Figure 6. The windscreen is simplified as a flat surface in the FE model in order to reduce computational time. The assumption of a flat surface is made based on the previous studies [6]. The windscreen and vertebrata are developed using 8-node (C3D8) linear solid elements while the rubber blade are developed using combination of 4-node (C3D4) and 8-node (C3D8) linear solid elements. The levers (primary, second and third) are developed using 4-node (C3D4) linear solid element while the wiper arm are developed using combination of 4-node (C3D4), 6-node (C3D6) and 8-node (C3D8) linear solid elements. Element types in brackets show the notation in ABAQUS nomenclature. Details for each of the components are given in Table 1.

(a)

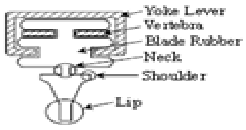


(b)

Figure 5: Windscreen wiper; (a) an actual wiper (b) FE model



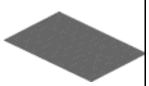
(a) Structural of wiper blade



(b) Cross section A-A figure

Figure 6: Details of wiper blade [4]

Table 1: Description of wiper blade components

Components		Types of element	No. of element	No. of nodes
	Windscreen	C3D8	1035	2208
	Rubber blade	C3D4 C3D8	75446	30802
	Vertebrata	C3D8	22	92
	Third levers (both side)	C3D4	13721	5025
	Second levers (both side)	C3D4	3388	1415
	Primary lever	C3D4	5712	2256
	Wiper arm	C3D8 C3D6 C3D4	4198	4930

The next development stage is to bring all components together to form an assembly model. A combination of tie element and self-contact/surface to surface contact element are used to represent contact interaction between wiper components and windscreen/rubber blade interface respectively. Table 2 shows details of windscreen wiper couplings that are used in the FE assembly model. Surface-to-surface contact interaction is used between windscreen and rubber blade in order to capture a realistic contact pressure distribution which is essential in the complex eigenvalue analysis. The neck and shoulder can deform largely due to force exerts on it and they may contact each other. Hence, self contact interaction is a suitable option to represent contact between the two geometries. Tie element is used to couple together between rubber blade and third lever, and third lever and second lever. For the third lever and second lever, the tie element is freely to rotate in its axial direction and it behaves like a hinge.

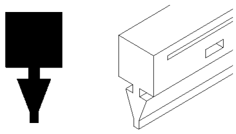
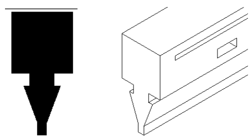
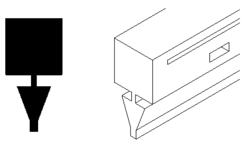
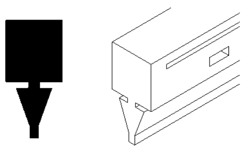
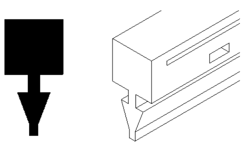
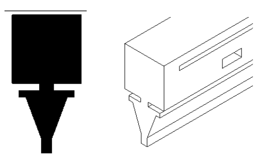
Table 2: Windscreen wiper model couplings

No.	Connections	Type of connection
1	Windscreen-rubber blade	Surface to surface
2	Neck-shoulder	Self contact
3	Rubber blade-third lever	Tie
4	Third lever-Second lever	Tie
5	Second lever-Primary lever	Tie
6	Primary lever-Wiper arm	Rigid body

3.2 Structural Modifications

In this section, various structural modifications are proposed in order to reduce chatter vibration of the wiper blade assembly. This can be achieved when the positive real parts of the complex eigenvalue of the baseline model are being reduced or eliminated. In this study, only rubber blade part is modified. There are five modifications of a new blade model (NBM) design are proposed to suppress the chatter generated in the wiper system. Details of the structural modification are given in Table 3.

Table 3: Proposed structural modifications

No.	Modification	Description
Baseline		Original wiper blade with a neck size 1mm width and 1mm height. It has no edge on both side of the blade shoulder.
NBM 1		The neck of the blade is thicker than the baseline design. The width is increased to 2mm.
NBM 2		The neck of the blade is thinner than the baseline design. The width is reduced to 0.5mm.
NBM 3		The height of the blade neck has been decreased from 1mm to 0.5mm.
NBM 4		The height of the blade neck has been increased from 1mm to 1.5mm.
NBM 5		An edge has been added in both side of the blade shoulder and the height of the neck has been decreased from 1mm to 0.5mm.

4. Results and Discussion

The results obtained from the experimental and FE method is utilized for comparison and validation. The first section presents the correlation between EMA and FE modal analysis results. Then, vibration results from experiment will be discussed. Next, complex eigenvalue analysis of baseline model is performed for the validation with the experimental results. Finally, complex eigenvalue analysis is performed on the modified wipers. A good modification should not produce any positive real parts.

4.1 Validation of FE Model

Results in Table 4 show that there are very good correlation between predicted and measured data for all wiper components. The results are based on the material data given in Table 5.

Table 4: Correlation of experimental modal analysis with FE analysis

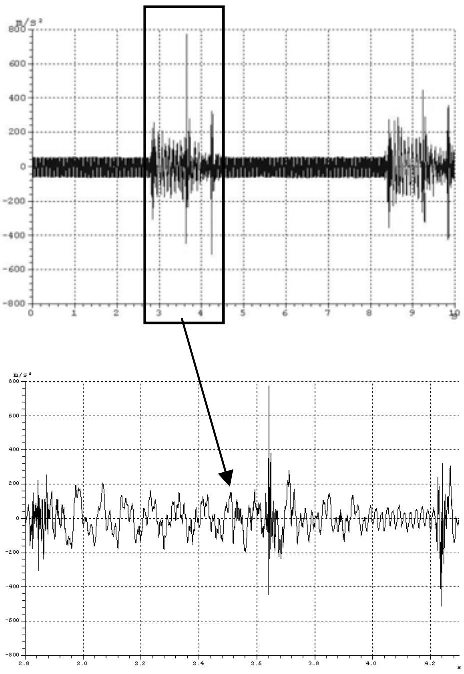
Component	Mode No.	Experimental Frequencies (Hz)	FE Analysis (Hz)
Windscreen	1	219	207
	2	242	248
	3	308	319
Rubber blade	1	61	42
	2	153	152
	3	286	281
Primary lever	1	247	247
Levers (second and yoke lever)	1	723	705
	2	835	857

Table 5: Material properties of wiper components

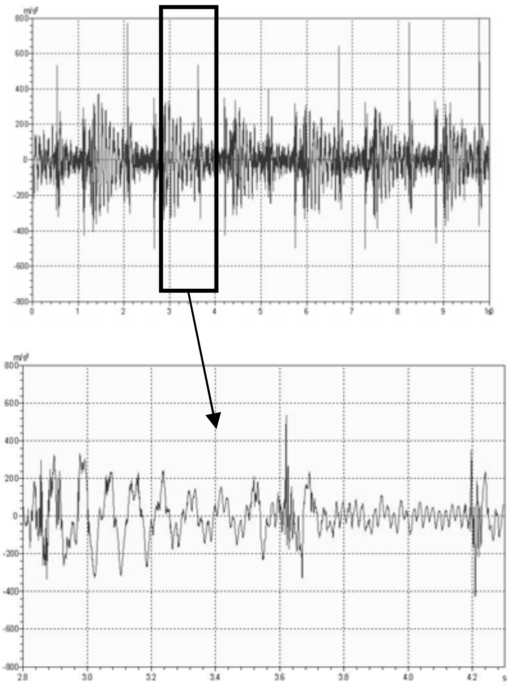
Component	Density (kg/m^3)	Young's Modulus (GPa)	Poisson's Ratio
Windscreen	2500	8.7	0.25
Rubber	1000	7.1e-3	0.49
Primary	7981	242.8	0.29
Levers	7981	464	0.29

4.2 Experiment of Noise and Vibration

For a wiper rotational speed of 1.8 rad/s, acceleration response is shown in Figure 7(a). It is seen that high vibration amplitude occurred rightly at the beginning and end of the wiper stroke. This may due to two reasons: stick-slip and/or negative velocity-friction characteristic mechanisms [6]. There is less idle time after one complete stroke for rotational speeds of 2.5 rad/s (Figure 7(b)), compared to 4s idle time for rotational speed of 1.8 rad/s.



(a) Average speed of 1.8 rad/s at Z direction



(b) Average speed of 2.5 rad/s at Z direction

Figure 7: Acceleration responses during wet condition

The above results are seen comparable to the findings of Goto et.al [2], where the vibration could easily be generated before and after wiper stroke as shown in Figure 8.

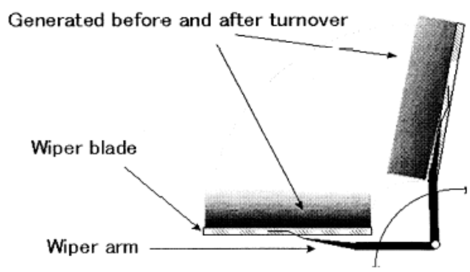
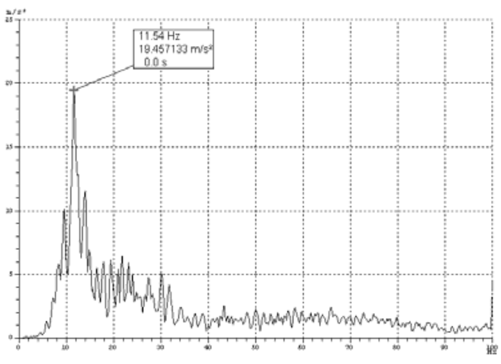
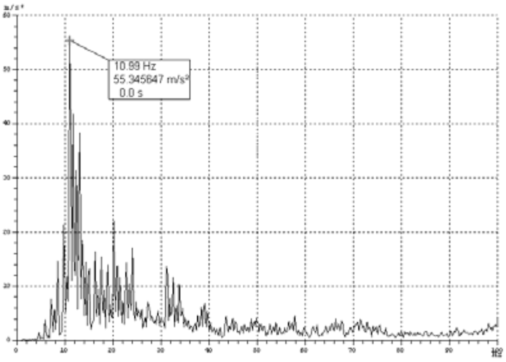


Figure 8: Location of noise generation [1]

From acceleration responses figure in Figure 9(a), it is found that at the wiper speed of 1.8 rad/s, the vibration is dominated at frequency around 12 Hz. For speed at 2.5 rad/s as depicted in Figure 9(b) vibration is generated at dominant frequency of 11 Hz. It seems that the vibration frequency of the wiper is almost the same for different speeds. From those measured frequencies, it can be said that current wiper system is experiencing chatter vibration.



(a) Average speed of 1.8 rad/s



(b) Average speed of 2.5 rad/s

Figure 9: Vibration frequencies measured from the rubber blade

4.3 Complex Eigenvalue Analysis

This section focuses on prediction of unstable frequency at a system level. Complex eigenvalue analysis can be a tool to trace the regions of the parameter space that lead to instability of the wiper blade system. For wiper chattering analysis, the most important source of nonlinearity is the frictional sliding contact between the windscreen and the blade. ABAQUS allows for a convenient, but general definition of contact interfaces by specifying the contact surface and the properties of the interfaces. ABAQUS has developed a new approach of complex eigenvalue analysis to simulate the disc brake squeal noise [12]. It is thought that this new approach can also be applied to study windscreen wiper chatter noise. It starts from preloading the blade pressure, rotating the wiper arm, and then extracting natural frequencies and complex eigenvalue, this new approach combines all steps in one seamless run. The complex eigenvalue problem is solved using the subspace projection method, thus a natural frequency extraction must be performed first in order to determine the projection subspace. The positive real parts of the complex eigenvalue indicate the degree of instability of the wiper assembly and are thought to indicate the likelihood of chatter occurrence. The higher the real part the more possibility the chatter noise to generate. The essence of this method lies in the asymmetric stiffness matrix that is derived from the contact stiffness and the friction coefficient at the blade/windscreen interface. Details of the complex eigenvalue formulation can be found in [13].

4.3.1 Baseline Model

First, complex eigenvalue analysis is performed on the baseline model. The frequency of interest is ranging up to 500 Hz and at two different average rotational speeds of 1.8 rad/s and 2.5 rad/s. Table 6 presents the results of unstable frequencies obtained from complex eigenvalue analysis for baseline model and the results from the experiment. From the analysis, it shows that there are more than one unstable frequencies predicted compared to one chattering frequency captured in the experiment. It is found that there are over-predictions in the simulation results even though one of the chatter frequencies is reasonably matched with the experimental data. From Table 6, it is also suggested that the different average speed of the wiper may not influence the vibration generated in the wiper system.

Table 6: Predicted results for baseline model

Exp.		FE	
Angular velocity ω = 1.8 rad/s			
Freq. (Hz)	Magnitude (m/s^2)	Freq (Hz)	Real parts
11.54	19.46	11.48	19.56
		44.38	52.53
		57.53	14.53
		77.82	14.78
		81.65	3.79
		98.63	8.93
Angular velocity ω = 2.5 rad/s			
Freq (Hz)	Magnitude (m/s^2)	Freq. (Hz)	Real parts
10.99	55.35	11.55	11.87
		45.99	35.27
		58.55	14.09
		78.45	13.67
		81.83	3.45

4.3.2 Structural modifications

The predicted unstable frequencies for different blade modifications are shown in Table 7. It is found that the rubber blade of the baseline model is characterized by a bending mode as shown in Figure 10. This agrees well with previous findings where Grenouillat et al [6] pointed out that the rubber blade vibrates essentially in a bending mode and Okura et al [3] believed that the chatter noise is significantly influenced by angle of attack of the blade. In order to reduce or avoid the chatter noise, it is suggested that the attack angle should be small and in turn to avoid the bending mode. From the predicted results NBM1, NBM4 and NBM5 can totally eliminate the chattering frequencies. It is due to the rubber blade of NBM1 and NBM5 do not form angle of attack (bending mode) whilst NBM4 does not show any mode at 11 Hz as illustrated in Figures 11(a), 11(e) and 11(d), respectively. For NBM4, it is believed that its chatter frequency has been shifted. However, modifications NBM 2 and NBM3 are still producing chatter frequency at 11.48 Hz. Figures 11(b) and 11(c) show that the rubber blade of these two modifications is characterized by bending mode and it is almost identical with the baseline model. From the predicted results, it is suggested that NBM1, NBM4 and NBM5 are the possible designs to reduce chatter noise.

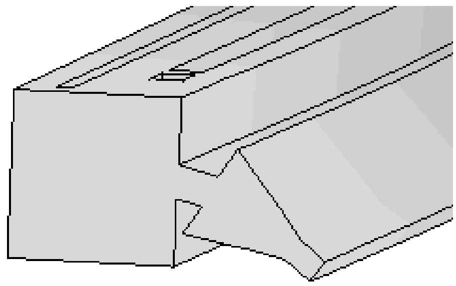


Figure 10: Bending mode of the rubber blade at 11.48 Hz

Table 7: Predicted results for different structural modifications

Exp.		Model	FE	
Freq (Hz)	Magnitude (m/s^2)		Freq (Hz)	Real parts
11.54	19.46	Baseline	11.48	19.56
			44.38	52.53
			57.53	14.53
			77.82	14.78
			81.65	3.79
			98.63	8.93
		NBM1	None	
		NBM2	11.46	9.45
			94.26	2.66
		NBM3	11.5	11.58
		NBM4	None	
		NBM5	None	

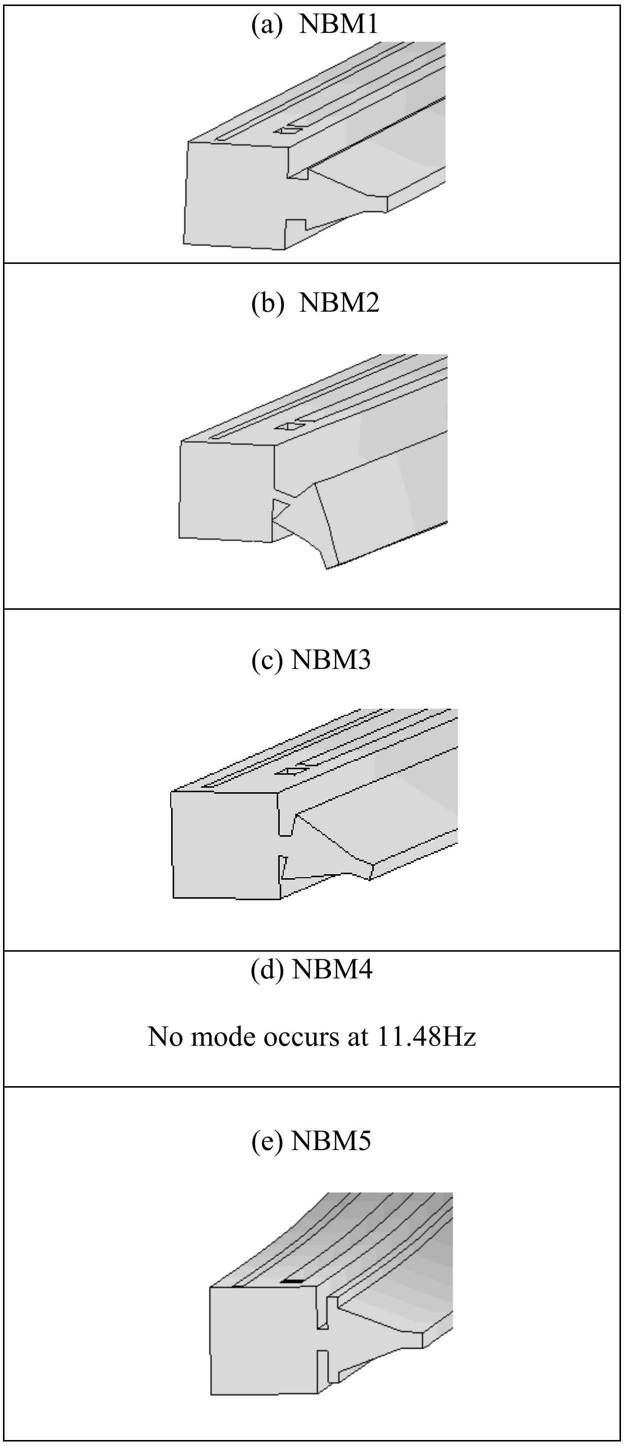


Figure 10: Mode of the rubber blade for different designs at 11.48 Hz

5. Conclusion

This paper presents an approach to predict wiper blade chatter noise using FE method. Complex eigenvalue analysis that made available in commercial software package, ABAQUS is used to predict chatter frequencies. From the experiment, the result shows that the windscreen wiper produces a low frequency noise called chatter, at dominant frequency of 11Hz. It is found that, at different wiper average speeds, the chattering vibration is generated before and after the wiper turnover. The complex eigenvalue analysis has been utilized in a finite element analysis to study chatter problem. The measured chatter frequency has been successfully replicated in the analysis. Initially, there are six unstable frequencies (chatter) appeared in the baseline model. It is found that the chatter noise at 11.48 Hz is characterized by bending mode of the blade. Based on the baseline results, various structural modifications have been proposed and simulated using complex eigenvalue analysis in order to suppress the chatter frequency. From the five proposed modifications, it is found that NBM 1, NBM 4 and NBM 5 can totally eliminate the positive real parts which indicate no chatter appears in wiper blade assembly. This indicates complex eigenvalue analysis can be used as a tool to predict vibration in the windscreen wiper.

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REFERENCES:

[1] Denso International Product Co., 2008, WiperTechnicalInformation,www.denso.sg/tpl/pdtlineup_wiper_technicalinfo.html (24 September 2008).

[2] S. Goto, H. Takashi, T. Oya, 2001, Clarification of Mechanism of Wiper Blade

Rubber Squeal Noise Generation, JSAE Review 22, 57-62.

[3] S. Okura, T. Sekiguchi, T. Oya, 2000, Dynamic Analysis of Blade Reversal Behavior in a Windshield Wiper System, SAE Technical Paper, 2000-01-0127.

[4] S. Okura, T. Oya, 2003, Complete 3D Dynamic Analysis of Blade Reversal Behavior in a Windshield Wiper System, SAE Technical Paper, 2003-01-1373.

[5] S. Goto, H. Takahashi, T. Oya, 2001, Investigation of Wiper Blade Noise Reduction Measures, SAE Technical Paper, 2001-01-1410.

[6] R. Grenouillat, C. Leblanc, 2002, Simulation of Chatter Vibrations for Wiper Systems, SAE Technical Paper, 2002-01-1239.

[7] B. Stallaert, F. Doucet, J. Rys, A. Diallo, S. Chaigne, J. Swevers, P. Sas, 2006, Application of Dither Control for Automotive Wiper Squeal, Proceedings of ISMA, 263-272.

[8] C.R. Chevennement, T. Dreher, P. Alliot, E. Aubry, J.P. Lainé, L. Jézéquel, 2007, Flexible Wiper System Dynamic Instabilities: Modelling and Experimental Validation, Experimental Mechanics, 47, 201–210.

[9] D.J. Ewins, 1984, Modal Testing: Theory and Practice, Research Studies Press, Letchworth.

[10] A.R. Abu Bakar, E. Jamaludin, C.Y. Leong, 2007, An Experimental Investigation into Noise and Vibration of an Automotive Wiper, Proceedings of the Regional Conferences on Advance in Noise, Vibration and Comfort, 261-269.

[11] H. Idris, 2007, Study of Windshield Wiper Noise, BEng Thesis, Department of Automotive Engineering, Universiti Teknologi Malaysia.

[12] A.R. Abu Bakar and H. Ouyang, 2006, Complex Eigenvalue Analysis and Dynamic Transient Analysis in Predicting Disc Brake Squeal, Int. J. Vehicle and Vibration, 2(2), 143-155.

[13] ABAQUS Analysis User's Manual, 2004, Version 6.5.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This project describes a method to evaluate noise and vibration characteristics of an automotive windscreen wiper system using finite element method. From the literature review, it is found that most of the previous researchers adopted experimental and analytical approaches but very few using numerical approach via finite element method in attempts to evaluate noise and vibration of the windscreen wiper. Previous researchers who used finite element method limit their studies to the modal analysis without continuing with the stability analysis to evaluate noise and vibration of the windscreen wiper. This project is seen to be the first to evaluate noise and vibration characteristics of the windscreen wiper using stability analysis via complex eigenvalue analysis.

The first stage of this project is to conduct modal testing in order to obtain natural frequency and its associated mode shape for each of the windscreen wiper components. This measured data is very useful to verify dynamic behaviours of the finite element model. Another experiment on noise and vibration of the windscreen wiper is carried out. It is found that the windscreen wiper produces approximately 11 Hz noise which is classified as chatter. It is also found that similar chatter frequency is measured regardless of speed and weather conditions. It is observed that chatter noise is generated before and after wiper stroke. It is also observed that the wiper has steady motion in the middle of rotating stroke for the dry condition compared to the wet condition, which non-uniform water films on the windscreen may disturb contact between the rubber blade and the windscreen interfaces.

The second stage of the project is to develop a validated three dimensional finite element (FE) model of a real windscreen wiper and analyse its stability. First, the FE model is validated using modal analysis i.e. by comparing natural frequency and mode shape with the measured. Having satisfied with the validation results all windscreen wiper components are brought together to form an assembly model. Proper couplings and contact interactions are applied to the assembly model so that it can replicate the real assembly of the wiper. Stability analysis via complex eigenvalue is used to evaluate noise and vibration of the wiper. The positive real parts of the complex eigenvalue indicate the degree of instability and hence likelihood for the wiper to generate noise and vibration. It is found from predicted result that the wiper produces positive real part at approximately 11 Hz which is almost identical to the measured data. It is seen that this frequency is characterised by bending mode of the rubber blade.

The last stage of the project is to proposed suppression of noise and vibration of the windscreen wiper. Having known the noise and vibration characteristics of the windscreen wiper, i.e. chatter noise and bending mode of the rubber blade, it is essential to modify this component. Various modifications are proposed and it is found that three of them are capable of preventing chatter noise where bending mode that forms in the baseline model has been shifted away from 11 Hz. It is also found that different shapes of the blade model will produce different attack angles. The attack angles are not consistent, thus it is suggested that the attack angle does not contribute to the noise generated in the wiper.

Overall, the specific objectives of the project are met. A validated FE model has been successfully developed and stability analysis of the FE model via complex eigenvalue has been performed. Good correlation is found between prediction and measured data. Noise and vibration characteristics of the windscreen wiper is captured and predicted. A few suggested modifications that capable of preventing noise and vibration are obtained.

6.2 Recommendations for Future Works

For future work, several recommendations are given as follows:

i. Use curve windscreen as real as actual wiper system to improve the accuracy of the result.
ii. Include water film that separating rubber blade and windscreen interfaces in the simulation to investigate whether the water film is the factor to disturb wiper operation.
iii. To simulate the FE model using dynamic transient analysis in order to assess mechanism of the noise and vibration
iv. In order to verify effectiveness of the proposed modifications in the FE model real modified rubber blades must be fabricated and tested.

REFERENCES

ABQUS Theory Manual Version 6.4, Hibbit, Kalsson & Sorence, Inc., 2003

Abu Bakar A R, A Sharif, M Z A Rashid, and Ouyang H. (2007). Brake Squeal: Complex Eigenvalue versus Dynamic Transient Analysis. *SAE Technical Paper*, 2007-01-3964.

AbuBakar A. R. and Ouyang H. (2006). Complex Eigenvalue Analysis and Dynamic Transient Analysis in Predicting Disc Brake Squeal. *Int. J. Vehicle Noise and Vibration*, Vol. 2, pp. 143-155.

AbuBakar A. R. *Disc Brake Squeal- A Prediction Methodology*. Germany: VDM Verlag Dr. Müller e. K.

AbuBakar A. R., Jamaluddin E., and Leong C. Y. (2007). An Experimental Investigation into Noise and Vibration of an Automotive Wiper. Proceeding Conference on Advances in Noise, Vibration and Comfort (NVC) 2007, pp. 261-269.

B. Stallaert, F. Doucet, J. Rys, A. Diallo, S. Chaigne, J. Swevers, P. Sas. (2006). Application of Dither Control for Automotive Wiper Squeal. *Proceeding of ISMA* 2006, pp. 263-272.

C. Chevennement-Roux·T. Dreher·P. Alliot·,and E. Aubry·J.-P.Laine·L.Jezequel. (2007). Flexible Wiper System Dynamic Instabilities: Modeling and Experimental Validation. *Experimental Mechanics* 47, pp. 201-210.

Denso Product Co. Retrieved on November 20, 2007, from www.denso.com.sg/tpl/pdtlineup_wiper_technicalinfo.htm.

Goto S., Takahashi H., and Oya T. (2001). Clarification of the Mechanism of Wiper Blade Rubber Squeal Noise Generation. *JSAE Review* 22, pp. 57-62.

Goto S., Takahashi H., and Oya T. (2001). Investigation of Wiper Blade Squeal Noise Reduction Measures. *SAE Technical Paper*, 2001-01-1410.

Grenouillat R., and Leblanc C. (2002). Simulation of Chatter Vibrations for Wiper Systems. *SAE Technical Paper*, 2002-01-1239.

Grenouillat R., and Leblanc C. (2002). Simulation of Mechanical Pressure in a Rubber-Glass Contact for Wiper Systems. *SAE Technical Paper*, 2002-01-0798.

H. Ouyang, W. Nack, Y. Yuan, and F. Chen. (2005). Numerical Analysis of Automotive disc Squeal: A Review. *Int. J Vehicle Noise and Vibrations*, 1 (3/4), pp. 207-230.

Hasbullah bin Idris. (2007). *Study of Windshield Wiper Noise*. Bachelor Degree Project, Universiti Teknologi Malaysia, Skudai.

Inman, D. J. (2001). *Engineering Vibration* (2nd Edition). New Jersey: Prentice Hall.

Kinkaid, N.M., O'Reilly, O.M. & Papadopolous, P. (2003). Review of Automotive Disc Brake Squeal. *Journal of Sound and Vibration*, 267, pp. 105-166.

Mahajan S. K., Yu-Kan H., and Zhang K. (1999). Vehicle Disc Brake Squeal Simulations and Experiences. *SAE Technical Paper*, 1999-01-1738.

Matweb Material Property Data for AISI 1005 Steel. Retrieved on October 11, 2007, from http://www.matweb.com/search/DataSheet.aspx?MatID=6773.

Matweb Material Property Data for Aluminum. Retrieved on October 11, 2007, from http://www.matweb.com/search/DataSheet.aspx?MatID=134.

Niw C. C. (2007). *Finite Element Model of Welded Joints in a Simple structure*. Bachelor Degree Project, Universiti Teknologi Malaysia, Skudai.

Okura S. and Sekiguchi T., and Oya T. (2000). Dynamic Analysis of Blade Reversal Behavior in a windshield Wiper System. *SAE Technical Paper*, 2000-01-0127.

Okura S., and Oya T. (2003). Complete 3D Dynamic Analysis of Blade Reversal Behavior in a Windshield Wiper System. *SAE Technical Paper*, 2003-01-1373.

Shun C. C., and Hai P. L. (2004). Chaos Attitude Motion and Chaos Control in an Automotive Wiper System. *International Journal of Solids and Structures* 41, pp. 3491-3504.

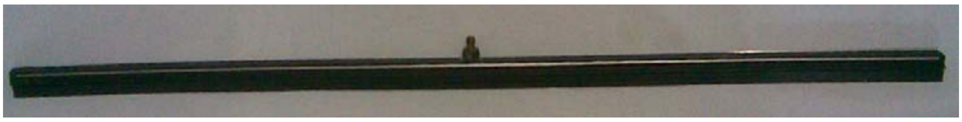
Shun C. C., and Seng C. C. (2006). Dither Signals with Particular Application to the Control of Windscreen Wiper Blades. *International Journal of Solids and Structures* 43, pp. 6998-7013.

Zhao S. M., Dharani L. R., Chai L. and, Barbat S. D. (2006). Analysis of Damage in Laminated Automotive Glazing Subjected to Simulated Head Impact. *Engineering Failure Analysis* 13, pp. 582-597.

APPENDIX A

PHOTOGRAPHS OF THE EXPERIMENT

Proton Iswara’s Windscreen



Wiper Blade

Levers

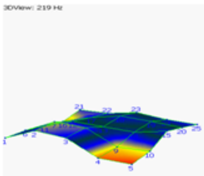
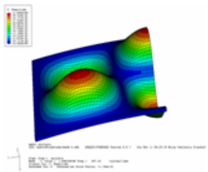
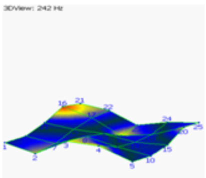
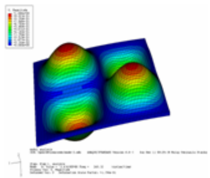
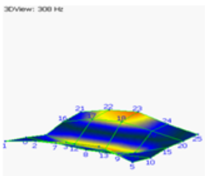
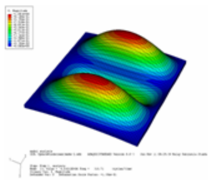
Tri-axial Attached in the Primary Yoke

Pipe Hose Attached at the Car’s Roof

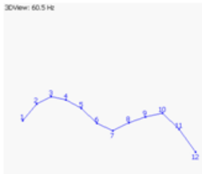
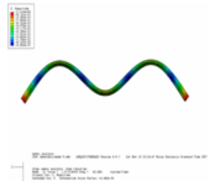
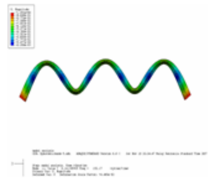
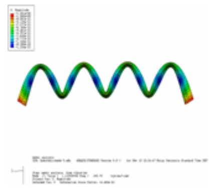
APPENDIX B

VALIDATION OF THE FE MODEL

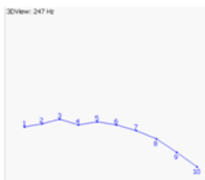
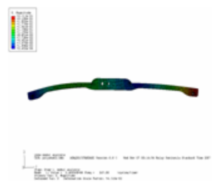
Comparison between EMA and FEA for Windscreen

Mode	Error (%)	EMA	FEA
1	5.35	 (219 Hz)	 (207.28 Hz)
2	-2.61	 (242 Hz)	 (248.32 Hz)
3	-3.48	 (308 Hz)	 (318.71 Hz)

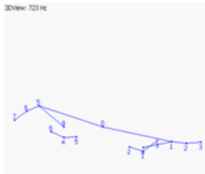
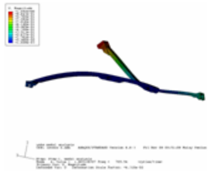
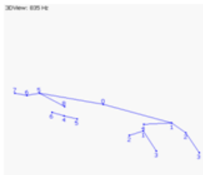
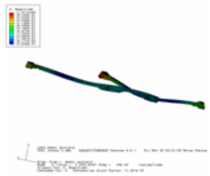
Comparison between EMA and FEA for Blade

Mode	Error (%)	EMA	FEA
1	-2.48	 (60.5 Hz)	 (42 Hz)
2	0.54	 (153 Hz)	 (152.17 Hz)
3	1.85	 (286 Hz)	 (280.7 Hz)

Comparison between EMA and FEA for Primary Lever

Mode	Error (%)	EMA	FEA
1	0	 (247 Hz)	 (247 Hz)

Comparison between EMA and FEA for Levers

Mode	Error (%)	EMA	FEA
1	2.41	 (723 Hz)	 (705.54 Hz)
2	2.61	 (835 Hz)	 (856.8 Hz)

APPENDIX C

ACHIEVEMENTS/OUTPUTS

LIST OF PUBLICATIONS

1. I.M. Awang, **A.R. AbuBakar**, B.A. Ghani, R.A. Rahman, and M.Z.M. Zain. 2009. Complex eigenvalue Analysis of Windscreen Wiper Chatter Noise and its Suppression by Structural Modifications, *Int. J. Vehicle Structures & Systems,* 1(1-3), 24-29.

2. I M Awang, C Y Leong, **A R AbuBakar**, R A Rahman, B A Ghani & M Z M Zain, *Modeling and simulation of automotive wiper noise and vibration using finite element method*, RiVET2008, July 2008, Kuala Lumpur.

3. I M Awang, **A R Abu-Bakar**, B Abd-Ghani, R Abd-Rahman, and M Z Md-Zain, *Modelling and Simulation of Wiper Noise and Vibration Using the Finite Element Method*, ICAME09, UiTM, Shah Alam (**BEST PAPER AWARDS**).

4. **Abd Rahim Abu Bakar,** Leong Chin Yin & Elfandy Jamaluddin, *Experimental investigation into noise and vibration of an automotive wiper*, NVC2007, UKM, Bangi.

NO. OF STUDENT

MEng Student

1. Ibrahim Marzukie Awang, *Finite element analysis of windscreen wiper chatter noise,* December 2007- October 2009.

BEng Student

1. Leong Chin Yin, *Modelling of simulation of a wiper blade noise and vibration*, BEng Thesis, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 2008.