International Journal of Modern Engineering Research (IJMER)
www.ijmer.com Vol.3, Issue.1, Jan-Feb. 2013 pp-199-203 ISSN: 2249-6645

Experimental Studies of Automotive Disc Brake Noise and Vibration: A Review

Amr M. Rabia, [1] Nouby M. Ghazaly, [2] M. M. Salem, [3] Ali M. Abd-El-Tawwab[4]
Automotive and Tractor Eng. Dept., Minia University, El-Minia - 61111, Egypt

ABSTRACT: *In the last few decades, there have been extensive studies on analysis and investigation of disc brake vibrations done by many researchers around the world on the possibility of eliminating brake vibration to improve vehicle users' comfort. Despite these efforts, still no general solution exists. Therefore, it is one of the most important issues that require a detailed and in-depth study for investigation brake noise and vibration. Research on brake noise and vibration has been conducted using theoretical, experimental and numerical approaches. Experimental methods can provide real measured data and they are trustworthy. This paper aims to focus on experimental investigations and summarized recent studies on automotive disc brake noise and vibration for measuring instable frequencies and mode shapes for the system in vibration and to verify possible numerical solutions. Finally, the critical areas where further research directions are needed for reducing vibration of disc brake are suggested in the conclusions.*

Keywords: *Noise and vibration, experimental investigations, automotive disc brake.*

I. INTRODUCTION

Since vehicle comfort has become such an important factor to indicate the quality of a passenger car, eliminating or reducing the noise and vibration of a vehicle structure and system seems to provide a leading edge in the market to vehicle manufacturers. With progress made towards other aspects of vehicle design refinement against vehicle vibration and noise through improvement, refinement in brake vibration and noise is inevitable. Research into understanding brake noise and vibration has been ongoing over the last 50 years or more. Initially drum brakes were studied due to their extensive use in early automotive brake systems. However, disc brake systems have been common place on passenger vehicles since the 1960s and are used more extensively in modern vehicles. It follows that research into brake noise and vibration became focused more onto disc brake systems. A schematic of a disc brake assembly is shown in Figure 1. A large flat circular plate disc, referred to as the brake rotor, is mounted to the wheel axle and rotates with the applied to the piston, the inner pad is forced against the brake rotor. The caliper housing itself "floats", i.e. is free to slide back and forth in the direction of the wheel axis, and moves in the opposite direction to the piston. Fingers on the caliper force the outer pad into contact with the other side of the rotor clamping it between the pads. The caliper assembly is constrained by the anchor bracket from moving about the wheel axis; hence a braking torque is generated. Variations to this arrangement exist, some including fixed calipers with pistons that act on both the inner and outer pads directly, but the sliding caliper is used on the majority of automotive brake systems.

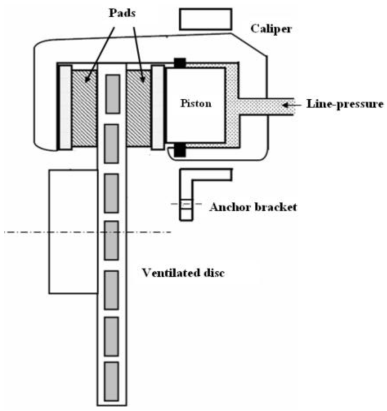

Figure 1 Schematic of a sliding disc brake caliper.

The rotor disc materials of a disc brake system are normally made from gray cast iron due to its excellent heat conductivity, good damping capacity and high strength [1–3]. Generally, the friction materials may be classified into four categories, metallic, metal ceramic, asbestos filled resin composites and asbestos-free composites. The friction pad materials are required to provide a stable coefficient of friction and a low wear rate at various operating speeds, pressures, temperatures, and environmental conditions [4–7]. Furthermore, these materials must also be compatible with the rotor material in order to reduce its extensive wear, vibration, and noise during braking [4].

There are many considerations in analyzing noise and vibration in automotive disc brake systems. During disc brake engagement, the brake lining rubs against the rotor and the kinetic energy is dissipated in the related friction process as a heat. This kinetic energy is transferred into the energy of the contact asperities, particles, and atoms [8]. Then, the energy of the motion of asperities, particles, and atoms translates into vibration and generates a sound wave [9]. The growth of friction layers affects the contact stiffness considerably and may cause the system to become instable [10]. Hoffmann and Gaul reported that surface properties (such as surface topography, roughness characterizations, physical properties of the interface, and the debris materials between the surfaces) may play significant role for the generation of vibration and noise [11].

A large number of papers have been published which contain models describing brake noise and vibration. There are typically three methods available to investigate brake vibration and noise, i.e., through experimental methods or analytical methods or numerical methods. Experimental methods can provide real measured data and they are trustworthy. Experimental approaches have been used to measure the brake frequencies and mode shapes for the system in vibration and to verify possible solutions that can eliminate or significantly reduce brake noise and vibration. This paper begins with an introduction to the automotive disc brake system, to give an overview of disc brake components and their function. A review of brake vibration literature is then presented that explains the disc brake vibration generated by friction. The scientific findings are categorized into the experimental investigations that have been employed to examine vibration problems.

II. EXPERIMENTAL APPROACHES

Over the years, experimental approaches using brake dynamometers or on-road tests have been widely used to examine the brake noise and vibration, to investigate the effects of different parameters and operating conditions, to understand the characteristics of the brake system during a vibration event and to verify possible solutions that can eliminate or reduce the vibration occurrence. The brake noise and vibration dynamometer has become the main testing platform for identifying propensity to generate noise during braking and for investigating brake vibration problems. There are two designs for the brake dynamometer. The first design is an inertia-type brake dynamometer that has flywheel attached to it and can be used to measure vibration at negative velocity slope. The second design is a drag-type brake dynamometer that can only test brake vibration at a constant speed.

It was typical to use a microphone and an accelerometer to capture sound intensity and vibration behaviour during vibration generation. Tarter [12] used these available tools to conduct a series of tests on noise and vibration with modified disc, friction material and pad contact geometry. From his experimental investigation, it was observed that slotted disc could eliminate squeal vibration while changes in friction material and pad contact geometry could have a significant effect in squeal vibration reduction.

Ichiba and Nagasawa [13] attempted to describe the cause of disc brake vibration using brake test rig. Small accelerometers were installed in the back plate, the disc and the friction material in order to measure its vibrational characteristics. They concluded that squeal vibration generation was dependent on the ratio of change in frictional force rather than in the friction - velocity characteristics where the exciting energy was derived from the fluctuations in surface pressure.

Felske et al. [14] were one of the first groups to use holographic interferometry to view the vibration modes on a self-excited disc brake. They present interferograms for two types of brake; a yoke and a fist type. The disc interferograms presented are self-excited (Double Pulsed Holography) and artificially excited (Time Averaged Holography). They suggested that the audible noise from a brake system comes from the pad and caliper, and not the disc as the noise from this destructively interferes in air.

Vadari et al. [15] discussed the future direction of disc brake noise testing. The discussion was focused on the on-vehicle data acquisition, integrated brake noise measurement system and dynamometer testing. They suggested the need for continued development of standardized methods for identifying and counting noise occurrences both on-and-off the road. The critical step to a true understanding of brake noise generation was to remove any subjective measurements from the counting process and adopting reliable and repeated descriptions of the brake noise propensity of a particular design. This could be achieved by using more robust on vehicle data acquisition, a simple and reliable brake noise dynamometer and a correct tool to visualise noise and vibration behaviour.

Bettge and Starcevic [16] carried out an experimental work on many samples of pads and discs using white light interferometry. They measured the topography of the surfaces quantitatively. They computed the distributions of area, height and slope of the contact patches. They described the influence of friction power and testing time. Their results show that high braking power leads to larger contact patches on the surface of the brake pads, the height of contact patches also increased and the contact patches are tilted towards the sliding direction.

Senatore et al. [17] conducted an experimental work on brake and clutch facing samples in sliding motion at different levels of loading, slip speed and sliding acceleration. They performed short time experiments using Pin-on-disc sliding contact in the laboratory test stand. They obtained a comprehensive view of the influence of the main sliding parameters by means of an artificial neural network. They investigated the not weak influence of the sliding acceleration to improve the friction coefficient prediction during transient operations. They concluded that the higher the sliding acceleration, the higher the friction coefficient. The materials have exhibited nearly linear dependence of the friction coefficient on the pressure contact in the studied ranges.

Nishiwaki et al. [18] examined the out-of-plane deformation of a rotating disc using the doubled pulsed technique in order to visualise the vibration pattern of the disc and pad when squeal vibration occurs. Their results show that squeal vibration was generated when both the rotating disc and pads vibrated in bending mode. They also concluded that squeal phenomena were strongly influenced by the natural frequencies and mode shapes of the disc.

Oliviera et al. [19] carried out an experimental work on brake squeal vibration instability. They investigated the dynamical and squeal vibration behaviors of a brake setup. They identified several characteristics that lead to instabilities and correlated them with the operating parameters. Their results indicated that the pad dynamics have a key role in the selection of the squealing modes at one of the out-of-plane eigen frequency of the system. They found that squeal vibration occurs at frequencies close to natural frequencies of the coupled system. In addition, the in-plane dynamics of the pad plays a key role in the squeal vibration mode selection. Squeal vibration does not require that a stick-slip limit cycle is established. Squeal vibration frequency is not globally affected by changes in relative velocity.

Oberst and Lai [20] conducted an experimental work using a noise dynamometer to determine the influence of geometrical parameters of brake pads on vibration. They evaluated the experimental results with a noise index and ranked for warm and cold brake stops. They analyzed the data using statistical description based on population distributions and a correlation analysis. They performed the correlation analysis between the time-averaged friction coefficient and peak sound pressure data by applying a semblance analysis and a joint recurrence quantification analysis. They compared linear measures with nonlinear measures based on statistical from the underlying joint recurrence plots. Their results indicated that pads with a single vertical slots or a single slot perform better than pads with no slots or double vertical slots.

Kemmer [21] experimentally investigated the friction layer between pad and disc and modeled it as a granular medium. In his simulations, he found the contact stiffness of the granular friction layer to be directly dependent on the particles' diameter, the shear modulus of the particles' material, the friction coefficient for the interactions among the particles, the normal force, and inversely dependent on the friction layer's thickness. With his experiments, he showed that for one friction material, higher pressures lead to smaller wear debris particles.

Fieldhouse and Steel [22] summarized an experimental work on varying mechanically induced offset center of pressure between the pad and rotor. They investigated the propensity of a brake to generate noise over a range of temperatures and pressures. Their results indicated that a mechanical instability which is not influenced by temperature or pressure is possible within a brake system. Such a mechanical instability is caused by 'spragging' of the system, which would encourage low-frequency noise generation. Pad abutment is important with a trailing abutment being found to be the most stable arrangement. The co-planar forces acting on the pad tend to promote a leading offset. At minimum friction for the pad-caliper abutment interface the o€ set tends towards the critical offset value. To promote stability a disc brake requires a high friction coefficient between pad abutment and caliper mounting bracket and a low friction material coefficient. The position of the mounting plane for the caliper carrier bracket is important because of its influence over the spragging angle. It needs to be as close to the plane of the disc rubbing surface as possible.

Eriksson et al. [23] conducted an experimental research in friction behavior and squeal vibration generation for four different disc brake pads at low speeds. They studied the influence of speed and pressure variation. The test included braking with continuously increasing and decreasing brake pressure at constant speed and vice versa. Their results indicated that no squeal vibrations were generated below a coefficient of friction of 0.4. Braking conditions with a high coefficient of friction were related to more frequent squeal vibration generation.

JOE et al. [24] carried out a theoretical and experimental work on a floating caliper disc brake system using a linear, lumped, and distributed parameter model. They investigated the dynamic stability by using the complex eigenvalues. Their work was done with a constant friction coefficient. Their results indicated that a small error between experimental and theoretical natural frequencies, the mode of the disc is significantly responsible of the frequencies of the disc brake vibration and noise as well as the mode of each component. The system is more unstable if the friction coefficient, lining stiffness, length of the pads, and thickness of the lining are large, the system is more stable if the Young's modulus and the mass of the disc and pads are large.

Abu Bakar and Ouyang [25] summarized a theoretical and an experimental study on wear prediction of friction material in a disc brake system. They investigated wear established on the surfaces of a new pair of brake pads under different duration of brake. They developed a three-dimensional finite element model of a real disc brake considering the real surface topography of the friction material. Their results indicated that the contact area of a new frictional material increases and initial rough surfaces later become smoother as wear progresses. The leading edge is prone to more wear than the trailing edge. The simulation result showed a reasonably good correlation with the experimental results in the static contact pressure distribution, and height distributions. Good agreement found between the unstable frequency predicting in the stability analysis and the vibration frequency recorded in the experiment.

Meziane et al. [26] carried out a theoretical and experimental work on a pad-disc tribometer. They did simulations for the pad-disc system to allow describing the instability phenomena that occur during the interface of two bodies in contact. They used a coulomb's friction law at the contact surface with constant coefficient. They showed the importance of the pad poission's ratio in the occurrence of the unstable state. Their results indicated that the contact surface of the pad can stick, slip or separate locally from the surface of the disc when instability occurs; these slip–stick–separation type contact waves generate impact forces that cause vibration. These waves give rise to periodic shocks in time and frequency, of which the fundamental frequency corresponds to a pad mode. This unstable mode is obtained by calculating the eigen modes and eigen frequencies of the system at rest and without taking friction into account. They reported that Poisson's ratio of the pad plays a basic role in the stability of the system since the latter becomes unstable beyond a threshold value.

Triches et al. [27] conducted a research to reduce noise from the disc brake systems using constrained layer damping. They studied the characterization of the noise generation via the brake dynamometer Figure 2. They measured the Pad, rotor and caliper Frequency Response Functions (FRF´s) by exciting each component with an impact hammer, and measuring the acceleration response with a small accelerometer. They carried out a modal analysis for rotor which supported by a foam block, in order to simulate the free-free boundary condition. They studied the behavior of brake components under pressure and temperature. They developed and tested an insulator bonded in the back plate. Their results indicated that a strong noise frequency around 7 kHz occur at a temperature of 150o and a pressure of 25 bar. The final dynamometer test showed reduction about of 20dB for some frequencies.

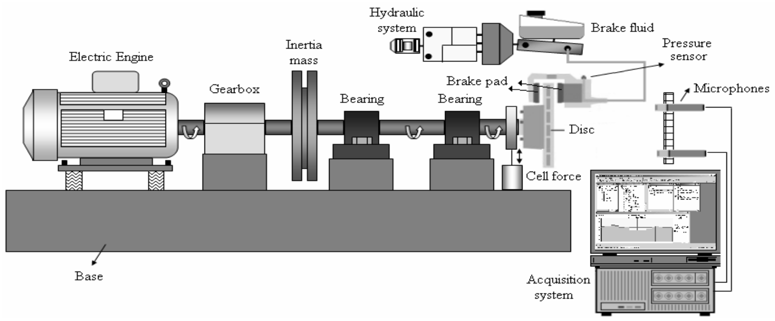

Figure 2 Components of an inertial dynamometer.

Oliviero Giannini et al. [28] carried out an experimental work to characterize the vibration and noise. They designed and built a laboratory brake for controlling experimental studies of noise emission in automotive brake as shown in Figure 3. They developed a relationship between modal and operational parameters of the system and emitted sound. They measured the relationship between the frequency of vibration emission and normal load. Their results indicated that an increase of the stiffness of the caliper affects the frequency of the vibration emission, shifting each zone to higher frequencies, but the motion of the whole system remains qualitatively the same.

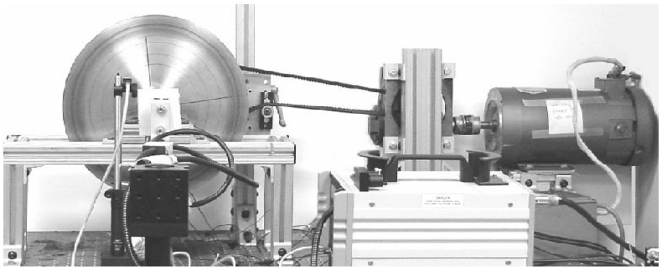

Figure 3 laboratory brake rig.

III. Conclusion

From the number of papers that have been published and summarized in this review, it is suggested that disc brake noise and vibration still continues to be a major concern for the automotive industry despite the efforts to reduce its occurrence during the past decades. Experimental methods will still play an important role for a number of reasons. Firstly, they offer more effective analysis tools than numerical methods. Secondly, diagnosis of the cause of brake vibration problems can often only be found by experimentation. Moreover, they can provide real measured data and they are trustworthy. Finally, the verification of solutions to noise and vibration problems can be achieved through experimental tests under different braking operating conditions. The previous experimental results reveal that there are numerous factors that influence the occurrence of vibration and noise in automotive disc brakes including materials and geometry of brake components, component interaction and many operating and environmental condition. All of these issues suggest that there is a strong need for further research to enhance our understanding of various parameters behind vibration generation.

IV. Acknowledgements

The authors would like to thank the FAW industry Group, manufacturing and trading of friction products in Egypt and Minia University for their continuous support in the research work.

References

Journal Papers:

[1] P.J. Blau, and J.C. McLaughlin, Effects of water films and sliding speed on the frictional behavior of truck disc brake materials, Tribol Int 36, 2003, 709–15.
[2] K.W. Liew, and N.S.M. El-Tayeb, The effect of rotor disc material on tribo behavior of automotive brake pad materials, Surf Rev Lett 15(5), 2008, 625–33.
[3] M. Eriksson, F. Bergman, and S. Jacobson, on the nature of tribological contact in automotive brakes, Wear 252(1–2), 2002, 26–36.
[4] S.J. Kim, and H. Jang, Friction and wear of friction materials containing two different phenolic resins reinforced with aramid pulp, Tribol Int 33, 2000, 477–84.
[5] M.G. Jacko, and S.K. Rhee, Brake linings and clutch facings, Kirk – Othmer encyclopedia of chemical technology, 4th ed., 4. New York: Wiley; 1992.
[6] M.G. Jacko, P.H.S. Tsang, and S.K. Rhee, Automotive friction materials evolution during the past decade, Wear 100, 1984, 503–515.

[7] M.H. Cho, S.J. Kim, D. Kim, and H. Jang, Effects of ingredients on tribological characteristics of a brake lining: an experimental case study, Wear 258, 2005, 1682–7.

[8] F. Chen, and C. A. Tan, and R. L. Quaglia, Disc brake squeal-mechanism, analysis, evaluation and reduction/prevention, Warrendale, Pa.: 2006, SAE International.

[9] I. Singer, and H. Pollock, Fundamentals of friction, Kluwer Academic publishers, Barunlage, Harx, Germany, 1992.

[10] M. Paliwal, Development of a friction layer model for the brake pad-rotor interface for noise and vibration, Southern Illinois University at Carbondale, Ph.D. thesis, 2003.

[11] N. P. Hoffmann, and L. Gaul, Friction induced vibrations of brake: research fields and activities, SAE international (08BC-0033), 2008.

[12] J. H. Tarter, Disc brake squeal, S.A.E. Technical Paper 830530, 1983.

[13] N. Ishihara, M. Nishiwaki, and H. Shimizu, Experimental analysis of low frequency brake squeal noise, S.A.E. Technical Paper 962128, 1996.

[14] A. Felske, G. Hoppe, and H. Matthai, Oscillations In Squealing Disk Brakes – Analysis Of Vibration Modes By Holographic Interferometry, SAE Paper No. 780333, 1978.

[15] V. Vadari, and M. Albright, An introduction to brake noise engineering, sound and vibration, Vol35-7, Roush Industries Inc., Livonia, Michigan, 2001.

[16] D. Bettge and J. Starcevic, Topographic properties of the contact zones of wear surfaces in disc brakes, Wear, Vol. 254, 2003, 195-202.

[17] A. Senatore , V. D'Agostino , R.DiGiuda and V. Petrone , Experimental investigation and neural network prediction of brakes and clutch material frictional behavior considering the sliding acceleration influence, Tribology International, Vol. 44, 2011, 1199-1207.

[18] M. Nishiwaki, H. Harada, H. Okamura, and T. Ikeuchi, Study on disc brake squeal, S.A.E. Technical Paper: 890864, 1989.

[19] G. Oliviera, A. Akay and F. Massi, Experimental analysis of brake squeal noise on a laboratory brake setup, Journal of Sound and Vibration, Vol. 292, 2006, 1-20.

[20] S.Oberst and J.C.S. Lai, Statistical analysis of brake squeal noise, Journal of Sound and Vibration, Vol. 330, 2011, 2978-2994.

[21] H. A. Kemmer, Investigation of the Friction Behavior of Automotive Brakes through Experiments and Tribological Modeling, PhD thesis, Universität Paderborn / Robert Bosch GmbH, Schriftenreihe ISBN 3-00-011230-8, 2002.

[22] J. D. Fieldhouse and W. P. Steel, A study of brake noise and the influence of the centre of pressure at the disc/pad interface, the coefficient of friction and caliper mounting geometry, Automobile Engineering, part D, Vol. 217, 2003.

[23] M. Eriksson and S. Jacobson, Friction behaviour and squeal generation of disc brake sat low speeds, Proc Instn Mech Engrs, Part D, Vol 215, 2001.

[24] Y.-G. JOE, B.-G.CHA, H.-J SIM, H.-J. LEE and J.-E. OH, Analysis Of Disc Brake Instability Due To Friction-Induced Vibration Using A Distributed Parameter Model, International Journal of Automotive Technology, Vol. 9, No. 2, 2008, PP. 161-171.

[25] A. Abu Bakar and H. Ouyang, Wear prediction of friction material and brake squeal using the finite element method, Wear, Vol. 246, 2008, 1069-1076.

[26] A. Meziane , S. D'Errico , L. Baillet and B. Laulagent, Instabilities generated by friction in a pad-disc system during the braking process, Tribology International, Vol. 40, 2007, 1127-1136.

[27] M. Triches Jr, S. N. Y. Gerges and R. Jordan, Reduction of squeal noise from disc brake systems using constrained layer damping, J. of the Braz. Soc. of Mech. Sci. & Eng, Vol. I, No. 3, 2004, 340-348.

[28] G. Oliviero, X. Zhaoshun, and A. Akay, A laboratory brake for the study of automotive brake noise, IMAC-XX: Conference & Exposition on Structural Dynamics, 2002, pp. 548-551.

Biographies

Amr M. Rabia is an assistant lecturer in Automotive and Tractor Eng. Dept., Minia University, Egypt. He received his B.Sc. from Automotive and Tractor Eng. Dept., Minia University, Egypt in 2007. Presently, he is pursuing M.Sc. in Minia University. His areas of interests are finite element methods, noise and vibrations of vehicle.

Nouby M. Ghazaly is an assistant Professor in Automotive and Tractor Eng. Dept., Minia University, Egypt. He obtained his PhD from Anna University, Chennai, India in 2011. He has to his credit more than 22 research papers in the areas of vehicle dynamics, noise and vibrations and finite element methods. He is a Technical Committee Member and a Reviewer of several international journals and conferences. He is currently serving as a consulting engineer of ATALON for testing and consulting engineers, India.

Ali M. Abd-El-Tawwab is an Associate Professor and Head of Automotive and Tractor Eng. Dept., Minia University, Egypt. He has many international and notional journal and conference papers to his credit. he has around 26 years of experience in teaching and research in the areas of Vehicle Ride Comfort, Active Suspension System Design and Control, Noise and Vibration Control, Computer Programming, Vehicle Mathematical Modeling and Vehicle Performance.