Prediction and Reduction of Automotive Disc Brake Squeal

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ABSTRACT

This paper concentrates on automotive disc brake squeal among other brake noises. Brake squeal noise has been one of the major problems which are yet to solved completely. It has been troubling the manufacturers and dealers because of the loss they suffer through customers' complaints. Designing and analysis the brake squeal system is very difficult, because of the uncertain environmental conditions and too many interacting variables. Factors like thermal excitation, contact pressure, structural stiffness, mode locking, eigenfrequencies, various theories and phenomenon are discussed. Different methods for analysis and optimization are mentioned that help to extract the value of squeal propensity. Along with this, probable solutions while designing and practical remedies are discussed.

Keywords*: Brake squeal, mode coupling, eigenvalue analysis, negative slope effect, thermal excitation.*

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1. Introduction

Disc brake squeal is one of the major problems that trouble automobile manufacturers. There are different types of brake noises like judder, groan, howl, low-frequency squeal, and high-frequency squeal. Brake judder is an outcome of forced vibrations while other noises result from self-excited vibrations. Xu Wang[1] classified brake noise according to frequency bandwidth as Judder 0-100 Hz, Groan 100-500 Hz, Howl 500-1000 Hz, Low-frequency squeal 1000-3000 Hz, and High-frequency squeal 3000-16000 Hz. Roberto Jordan[2] stated that failure modes of low-frequency squeal can be associated with the modal coupling of corner components which produce optimum condition for squeal while high-frequency squeal can be due to coupled resonance of components. The root cause of brake squeal has not been identified yet because the system is non-holonomic. It means that its state depends upon the path taken to achieve it. The system evolves along the path in which the parameters vary continuously. Such constraints cannot be represented as a potential function. Similarly, chaotic interactions and uncertainties create a major challenge while modelling and predicting squeal propensity.

According to Renault[3], parameters such as material properties, the coefficient of friction, geometric characteristics, are not accurately known at all conditions and their variations can cause instability in the equilibrium position, contact pressure between pad and rotor, etc. Also, the environmental conditions vary continuously and are difficult to simulate. Hence, uncertainty factor should be inserted while performing the analysis. Generally, a robust optimization method is used to seek a certain measure of robustness against the existing uncertainty in the system. It can be represented as deterministic variability in the value of parameters and convergence towards feasible design is more. A deterministic system means the absence of randomness. If the initial condition is known, the final condition can be predicted theoretically. But in practicality, the system is chaotic and hence it is highly sensitive to the initial condition. A small change in initial condition could yield diverging results. This sensitivity can be measured by using Lyapunov exponent. If the maximum Lyapunov exponent (MLE) is positive, the system is chaotic. Often probabilistic models are designed to quantify the uncertainty in the true value of a parameter by using probability distribution functions. Another type of optimization method is stochastic optimization. This method generates random variables

and makes use of them in the formulation of an optimization problem. It includes random objective function or random constraints, random iterates, etc. Dejie Yu[4] suggested that for better optimization results, thickness parameter of the backplate should be considered as design variable and it should be constrained not to be less than the initial value.

2. Factors affecting squeal

Xu Wang[1] mentioned the major factors that affect disc brake squeal as: rough finishing on resurfaced disc, loose fittings of brake pad in caliper, improper tightening of bolts and nuts, pad or disc contamination, temperature variations, contact pressure, coefficient of friction, natural frequency of components, geometric design etc.

2.1 Vibrations and mode coupling

The findings from Jarvis and Mills model concluded by Kinkaid[5] were that the amplitude of vibrations during squeal seemed to vary about a mean position but phase also kept changing continuously. This infers that two or more frequencies of the same order of mode and different phase exist simultaneously and couple with each other. Thus, the presence of mode coupling was verified. As the coefficient of friction goes on increasing the modal vibration frequencies come closer to each other and chance of mode locking increases. When the friction coefficient reaches a critical value, suddenly by bifurcation, a new mode exists which consists all previous modes as a coupled pair[6]. If such modes generate frequencies which approach the natural frequencies of the components, it could cause resonance. Kim[7] found out that friction forces are not only unstable due to the coefficient of friction but also by normal contacting forces from vibration mode coupling. Tison[8] provided the FE equation which governs the dynamic system as:

$$M(a) + C(v) + K(u) + FNL(v) = F \qquad \dots (1)$$

Where,
M = mass of different components
C = damping coefficient
K = stiffness matrix
a = acceleration of grid nodes
v = velocity of nodes
u = displacement of nodes
FNL = non-linear contact forces depending on displacement of contact interface
F = static tangential contact effects

$$F_{NL}(u) = F_{NL}\text{-normal force}(u) + F_{NL}\text{-friction force}(u) \qquad \dots (2)$$
$$F = K(u0) + F_{NL}(u0) \qquad \dots (3)$$

K(u0) = non-linear static forces
FNL(u0) = contact loads dependent on static displacement.

Mathematically, mode coupling leads to an asymmetric stiffness matrix in the equation of motion contrary to a symmetric matrix due to structural stiffness[7]. Kinkaid[5] discovered that squealing frequencies are slightly lower than the natural frequencies of the rotor. Also during squeal, pads and backplate generally vibrate along with disc with equal amplitude. Squeal is mostly generated due to non-uniform distribution of contact pressure. Squeal can be excited if leading edge of the brake pad has more pressure concentration[5,9]. Some noises were due to bending vibrations in pad superimposed on torsional vibrations on trailing edge of the pad. The Unified Hypotheses by Chen[10] proposed that instantaneous attach and detach process in braking produced impulsive excitation. When impulsive excitation is less, and mode coupling is more, squeal is produced.

2.2 Negative slope effect

It was experimentally found out that if braking pressure is more, the frequency of squeal increases. This is because as pressure increases, the coefficient of friction increases[2]. The increase in braking pressure leads to high values of contact stiffness and thus increases squeal propensity[6]. The modal coupling theory introduces friction force is the equations which make the stiffness matrix asymmetric and the system unstable and hence needs to be solved by complex eigenvalue extraction[11]. Millner[12] performed complex eigenvalue analysis (CEA) on a model containing

brake rotor disc, pad and caliper and found out that squeal occurred only when the value of coefficient of friction was more than the cut-off value of 0.28. Also, squeal is induced when static coefficient of friction is higher than the dynamic friction coefficient or if dynamic coefficient of friction decreases with speed[5]. This phenomenon that the friction coefficient between pad and disc goes on decreasing with increase in speed is called as the negative-slope effect. Squeal increases if the gradient of this slope increases[13]. Results of holographic interferometry suggested that squeal is most likely to occur when slope of friction coefficient is negative than when friction coefficient is constant[5]. When the coefficient of friction is constant, squeal propensity depends on the stiffness of pad and thus indirectly on Young's modulus. When an FE model was developed in a comprehensive manner, it showed that not only mode coupling and negative-slope effect but also the gyroscopic effect in the disc influenced squeal. As gyroscopic effect increases with angular velocity, squeal propensity increases with speed. But when speed increases, friction coefficient decreases and thus squeal decreases due to negative-slope effect. Practically, latter is dominant than the earlier and hence outcome is decrease is squeal[14].

2.3 TEI and Surface Topography

Thermal expansion instability (TEI) is the uncertainty that is introduced in the system due to thermal effects that arise from friction between pad and disc. Localized thermal expansion causes instability between rate of wear and the rate of expansion of pad and rotor. Hence, there is a critical sliding speed below which TEI does not occur. It varies from system to system[5]. The temperature of pad and disc surfaces increases with increase in use of braking and it causes the metals to soften. As friction coefficient decreases, it goes below the cut-off value and degree of instability of vibrations is reduced. But, due to softening of metals, brake loss increases which is undesirable[2].

Tison[8] pointed out the experimental results of Chen, which showed that the areas with squeal were characterized by adhesively joined and rough asperities while areas without squeal had abrasive wear topography. The contact asperities that are formed on the surfaces are elastic in nature and hence they drag each other. This causes an addition of fatigue cycles to the existing impact forces. Squeal triggering with such low plasticity index means that the cracked asperities start to be torn apart. As long as the tearing process continues, squeal will persist[15]. Similar to asperities, when pad slides over the disc a film is formed consisting of wear residue which increases the coefficient of friction and thus increases squeal propensity. This film degenerates at a temperature between 100-300 degrees Celsius[5]. Bergmann's experiment concluded that squeal depends also on disc-pad geometry, stiffness, wear and properties of material

2.4 Mechanisms and Forces

A type of force which is generally forgotten while carrying out analysis is follower force. These forces depend on the speed, movement, or position of the body on which it is acting. Here friction force is the main contributor as a follower force. Another force which also acts on the system is the centrifugal force. But even if its magnitude is comparable, it is not considered as it affects the system only at high speed and squeal is not generated at high speed according to negative slope effect. Similarly, gyroscopic effect is also neglected as it is negligible at low speeds. Negative slope effect is one of the prime causes of squeal and it causes the "stick-slip" phenomena. It happens because of uniform stick motion (which accumulates energy) followed by non-uniform slip motion (which dissipates energy) like a violin[13].

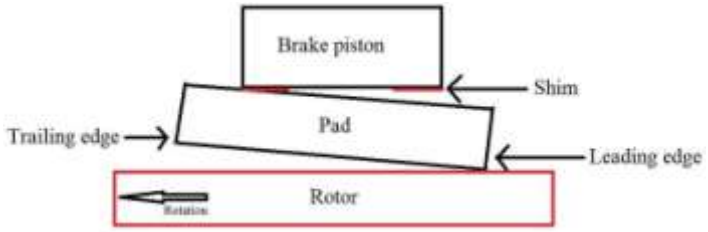

Fig-1: Sprag-slip phenomenon

Another consequence of negative slope effect is the "sprag-slip" phenomena, termed coined by Spurr (fig.1). Sprag-slip means oscillation between spragging and slipping. A perfect 90-degree angle of attack between pad and disc is not possible. It is always either an acute angle or an obtuse angle. This imperfection causes buckling of the pad which is known as spragging[8]. Stick-slip, sprag-slip and flutter instability highly contribute to squeal generation[16].

3. Methods to reduce squeal

The simplest theoretical solution to reduce squeal is to use surface material with coefficient of friction lower than the cut-off value. But it largely reduces braking performance and hence should not be employed. Results from the CEA can be used to reduce probability of squeal. The eigenvalue that is extracted is in the form of

$$\lambda = a + ib \qquad \ldots (4)$$

In equation (4), the real part is the degree of instability while the imaginary part is the eigen frequency multiplied by 2 Consider,

$$a = \mathrm{Re}[\lambda] \quad \text{and} \quad b = \mathrm{Im}[\lambda] \qquad \ldots (5)$$

then, squeal index[17] is given by equation (6)

$$\sigma = \sqrt{a^2 + b^2}.\sin(\tfrac{\delta}{2}) \qquad \ldots (6)$$

Where δ = phase angle

$$\delta = \tan^{-1}(\tfrac{b}{a}) \qquad \ldots (7)$$

Squeal index is a measure of squeal propensity. If $\sigma < 0.1$, squeal can be triggered[15]. Hence, while designing the brake system squeal index (equation 6) should be kept more than 0.1. Thus, smaller the value of real part of eigen mode, lower the instability and squeal propensity. If a > 0, the response is an exponential increase in oscillations, which is unwanted[7]. Roots of the equation of eigenvalues (equation 4) are assumed to be the stiffness matrix asymmetries arising due to follower forces[8].

Damping is also found to be effective against squeal generation. It is generally achieved from the multi-elastic layers in the shim (placed between backplate and caliper) which damps the bending waves[11]. When analysis was carried out considering damping, it was found that the critical mode frequencies which tend to couple, after damping they came close but did not combine (fig. 2 and 3) [7].

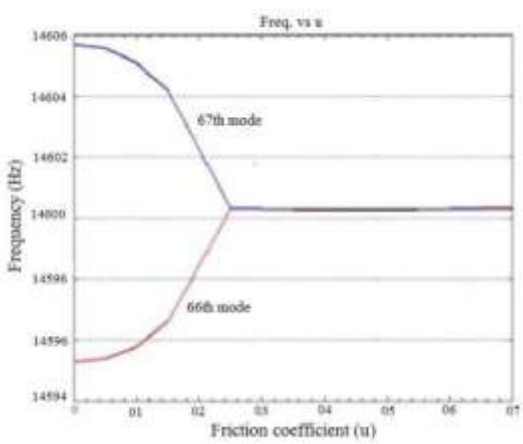

Fig-2: Undamped analysis[7]

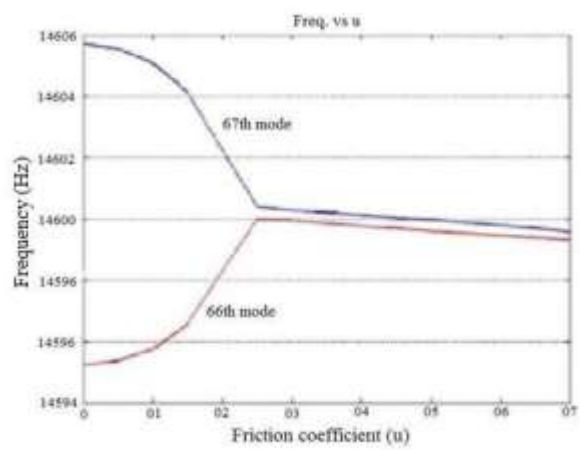

Fig-3: Damped analysis[7]

Damping might help in reducing squeal but it only minimizes out-of-plane vibrations. But the instabilities in the system occurring along the plane of the rotor still persist[18]. Pad chamfer decides the contact radius between the pad and disc surface which changes the mode shapes that occur due to self-excited vibrations. Radial chamfer (fig. 4) gives better performance than other types[7]. Kinkaid[5] mentioned that squeal can be reduced by elimination cooling fins, but it would cause overheating and might damage the components. But, changing the types of fins or vanes might help in reducing squeal. Kim [7] proved that curved-type vane (fig. 5) is more likely to reduce squeal than other types.

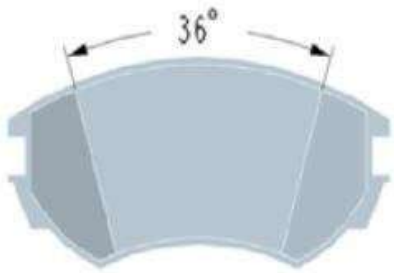

Fig-4: Radial chamfer[7]

Fig-5: Curved vanes[7]

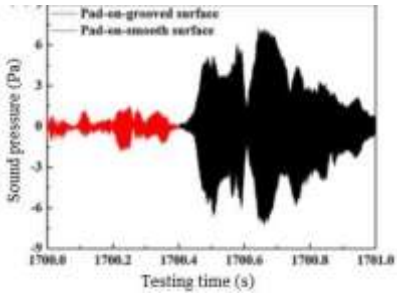

Fig-6: Effect of grooves[9]

Wang[9] carried out tribological analysis and found out that grooves if provided on disc surface, interrupt and distribute the concentrated contact pressure (fig. 6). It changes the high-pressure locations constantly. If the grooves are made wider, it results in low local contact stiffness which in turn avoids squeal locally. Sherif[15] also mentioned that squeal is avoided either when all elastic asperities on the surface are torn out, or asperities become plastic in nature.

Wagner[19] cited that splitting the generated eigen frequencies mathematically stabilized the system and reduced squeal. The range in which the double eigen frequencies should be split is an important parameter to be considered. Larger the gap between the frequencies, less the chance of mode coupling and more probability of avoiding squeal. For an extensive structural optimization of the brake disc including cooling vanes, the range should be properly quantified. Concentrating the optimization for whole audible range till 20kHz is inefficient. He experimentally found out that the minimal split between the double frequencies should be 60.2Hz. This is one of the most reliable and latest method to avoid squeal while modelling the brake system.
The most practical remedy to avoid squeal which is employed by automotive industries is using "brake noise insulators". It is a composite structure consisting of a thin ply of visco-elastic material sandwiched between two metal plates (fig. 7).

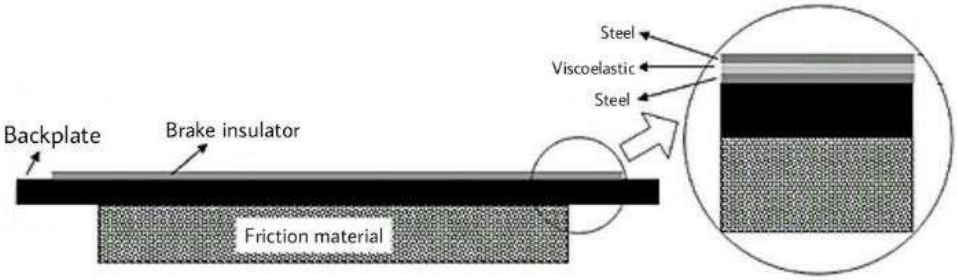

Fig-7: Brake noise insulators

It is either bonded adhesively or mechanically to the pad backplate. It absorbs vibrations from the pad and converts it into heat by shear damping. But, it also slightly increases the stiffness of the backplate. Backplate itself increases stiffness and increases squeal propensity. It is a crucial component in the brake assembly which should not be discarded.

Nouby's observations[6] implied that squeal can be reduced by decreasing the stiffness of backplate, that is by decreasing the Young's modulus. This is because the friction material connected to the backplate is softer. Higher the stiffness of backplate, more the uncertain deformation and vibration amplitude of pad, more the damping coefficient. Thus, an effective method to reduce squeal propensity is to use softer materials for the backplate.

4. Practical solutions

Experienced workers and drivers have suggested some causes and remedies. Causes include bent rotor, contaminations present on the disc, hardened surface due to overheating, etc. Workable solutions advised were braking hard to remove contaminations, filing the surface of the disc to remove the hard surface, boiling extra oil on the disc using a blow torch, use vibration shims between backplate and caliper, use different disc materials like Aluminium-matrix composites rather than Silicon Carbide.

5. Conclusion

Brake squeal system is an elusive topic. Due to chaotic interactions, uncertainty, etc. it becomes a non-holonomic system. Many researchers have found probable causes of generation of squeal viz. negative-slope effect, mode locking, stick-slip, sprag-slip, thermal excitation instability, etc. Several techniques like damping, introducing chamfer, changing the pattern of vanes, splitting double frequencies, modifying the backplate and using brake insulators do reduce the squeal propensity, but it still exists. Even after performing countless experiments and optimizations, the exact root cause of brake squeal has been a mystery. Smallest variations in operating temperature, contact pressure, rotor speed, the coefficient of friction may result in entirely diverging squeal propensity and vibration frequencies. Hence, proper modelling of boundary conditions even with robustness still remains a challenge. It is known that brake squeal will be generated if the coefficient of friction is greater than the critical value. But then why some systems do not produce squeal even if the coefficient of friction is more than cut-off value? Many questions like these still remain and hence this problem has no root solution yet, but hopefully, some research might provide us some ideas.

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