Improving the Ability to Simulate Noise from Brake Squeal

Multidiscipline Simulation playing a key role in reducing brake squeal noise and vibration
Brake Squeal Analysis

Background Information

The central tenet of a disc brake mechanism is to utilize friction between the pads and rotor to dissipate the vehicle’s kinetic energy in the form of thermal (50 kW at an interface) and brake squeal noise (over 100dB). The brake squeal is a sustained, high frequency (greater than 1000 Hz) vibration of brake system components during a braking action. These frequencies are within the entire audible range of the human ear (20 Hz - 16,000 Hz), which is discomforting to the vehicle occupants and leads to customer dissatisfaction, and thereby increased warranty costs. Brake squeal is one of the most challenging quality problems for automakers. Despite much research in the brake squeal event, there is still an incomplete understanding of the causes of brake squeal. This can be partly explained by the very complex nature of the brake squeal event itself and partly due to the way the automotive industry functions, i.e. where the research is not published in the peer-reviewed journals by industry engineers.

Essential Elements of Brake Design

In general, the brake disc is made of grey cast iron (excellent damping characteristics) and is shaped like a top-hat in order to protect the wheel bearings from the high temperatures induced during braking action at the rotor-pad interface. By designing brakes in this manner, the path for heat flow to bearings is increased, thereby minimizing the heating effect on bearings. In vented discs, cooling is further enhanced by constructing the disc from two discs connected by a series of vanes with alternating lengths (long and short) to further cause mode separation, thereby minimizing coupled vibration. Usually, prime numbers (17, 23, 31, 37 or 41) of vanes are used to reduce symmetric modes of vibration in the disc. In high performance and customized disc brakes, the rotors are often slotted and/or drilled to minimize adverse heating effects. The brake pad assemblies consist of a friction material which can be an integral part of a rigid pad backing plate. The friction material is usually a composite material made out of a matrix, which holds other components of the brake together: metallic fibers, frictional modifiers, and solid lubricants such as graphite.

Contributing Factors to the Brake Squeal Mechanism

Brake squeal happens due to the dynamic instability of the system and noise and vibration generated during braking. It is during this event that the rotor is the primary source of acoustics and its flat surface is what radiates sound even though the actual in-plane motion of the rotor is on the order of a few microns. One of the biggest contributors to brake squeal is the frictional interface between the rotor and brake pad,
as squeal excitation occurs at this friction interface. Increased coefficient of friction ($\mu$) between the rotor and pads increases the propensity for brake squeal.

The topography of the rotor and that of the brake pad play a crucial role in brake squeal. In addition, thermal effects play a big role in brake squeal. For instance, formation of hot spots can lead to thermal distortion of the brake pads as well as of the rotor which can lead to low-frequency instability (judder).

The rotor and brake pad have their own natural modes, but it is the overall system performance that an analyst is interested in. The modal frequencies and modal shapes of the rotor and pad will change once these parts are installed in a vehicle. During braking, the overall brake system is dynamically integrated with the axle which further changes the vibration and is far different compared to component level vibration.

**Strategies Employed to Minimize Brake Squeal**

Some of the strategies that are being used to minimize brake squeal are to increase rotor damping; change the rotor fins with long and short fins\(^1\) alternating to induce phase difference so the vibrations would not be coupled; using organic material dust or rubber filler in the brake pad or combining two or more abrasive materials with different hardness; using graphite lubricants, and/or reducing the tendency of the brake pad to absorb water as it increases the coefficient of friction. By designing the brake pads and rotor such that their natural frequencies in the audible range are as different from each other as possible can also suppress squeal\(^2\)\(^3\). Another method that is being utilized to eliminate squeal is to use dither - a high-frequency disturbance to minimize the effects of frictional forces\(^4\).

**Brake Squeal Theories**

There are two theories that describe brake squeal: 1) Stick-slip and creep slip, and 2) modal lock-in or coupling where two modes coalesce to form a complex unstable mode. Rotor-in-plane mode squeal creates high frequency squeals. At the first three tangential model frequencies these are usually around 6-7 kHz, 10-11 kHz and 14-15 kHz depending on rotor size. Therefore, it is important to minimize rotor tangential modal

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instability tendency and also keep it from coupling with out-of-plane mode to form a complex unstable mode.

**Brake Squeal Solutions**

Several testing techniques exist to physically verify brake squeal: 1) laser vibrometer ODS (operational deflection shape), 2) accelerometer, or 3) holographic interferometry to measure deflection. While experimental methods still play an important role in brake squeal analysis, CAE methods provide increasingly more insight into prediction of brake squeal. CAE methods help reduce the cost of physical prototypes while providing more insight into the system behavior and enable what-if studies before final system design.

**Multi-Discipline Solutions for Brake Squeal**

MSC.Software is developing leading technologies to address the complex brake squeal phenomenon with Multi-Discipline (MD) simulation tools. MD Nastran and MD Adams from MSC.Software provide a uniquely multidisciplinary solution for brake squeal simulation, with capabilities that span linear and nonlinear statics, linear and nonlinear dynamics, modal and frequency analysis, thermal analysis, multi-disciplinary optimization, and comprehensive system motion simulation. Together, MD Nastran and MD Adams provide a complete integrated solution to address the many challenges of brake squeal simulation.

With the help of MD Nastran, engineers are able to achieve more accurate results in less time and with less effort. For example, time-dependent loads on the brake system can be determined from a multi-body vehicle motion analysis, including flexible components and contact in the motion simulation for more accurate prediction of overall brake system performance. These loads can then be used to perform a detailed finite element analysis of the brake system, using the same data model and within a common solver framework for real end-to-end simulation. Manual data transfers and translation between the motion and structural solvers are avoided in MD simulation, resulting in higher simulation accuracy and overall efficiency.

Thermal conditions including conduction, convection, radiation, and advection can be accounted for in a multi-disciplinary solution, as well as complex eigenvalue analysis. For cost reduction and improved performance, MD Nastran provides a multi-disciplinary optimization solution, enabling engineers to perform shape, size, and topology optimization for optimum performance under a wide variety of specified design constraints, including material properties and modal response. The unique integration of motion, structural, non-linear, thermal, modal, and optimization technologies all within a common data model and common solver framework results in a complete end-to-end, multi-discipline system solution for brake squeal problems.
In the challenging area of brake squeal analysis, MSC.Software continues to invest in developing technologies that benefit customers with improved accuracy, reliability, and efficiency. Some of the key technical features that brake squeal simulation can benefit from today with MD solutions from MSC.Software include robust nonlinear structural analysis with frictional contact, complex eigenvalue analysis, and optimization.

Accurate prediction of potential brake squeal modes requires simulation of nonlinear contact between the brake pads and the rotor to account for the effect of the load generated when the brake pads squeeze the rotor. Figure 1 shows a typical MD Nastran model of a rotor and brake pad system. The easy to use contact modeling functionality and comprehensive nonlinear materials library in MD Nastran allows engineers to quickly and accurately simulate the load generated when the pads are in contact with the rotor.

![Figure 1. Typical brake system finite element model](image)

The MD end-to-end brake squeal simulation consists of complex eigenvalue analysis at selected contact load levels determined in the nonlinear contact analysis. The complex eigenvalue solution is performed with MD Nastran’s complex Lanczos eigenvalue solver. This complex eigenvalue solver, along with the standard Lanczos and Hessenberg solvers, is part of MD Nastran’s industry leading eigenvalue extraction technology. The influence of friction is accounted for in the complex eigenvalue solution by generating a contact stiffness matrix representing the contact between the pads and rotor at different coefficients of friction. In this manner, the effects of variable friction can be quantified in a single, integrated, multi-disciplinary simulation, avoiding the traditional need for separate nonlinear contact analyses for pad loads along with separate eigenvalue analyses and data transfer for each friction value of interest. The MD solution allows engineers to accurately and efficiently identify brake system scenarios showing the tendency for the coalescence of two vibration modes, signaling the onset of brake squeal.
As an example, consider the typical brake assembly with two pads and a rotor of Figure 1. Frictional contact between the pads and rotor is defined in MD Nastran, without the need for prior knowledge of the potential contact regions. A variety of contact friction scenarios between the pads and rotor can be simulated, including frictionless contact, a specific value of friction coefficient, or glued contact, which simulates perfect sticking with no slippage between the pads and rotor. Complex eigenvalue extraction is then performed to determine eigenvalues and mode shapes at the various frictional contact load conditions between the pad and rotor. Figure 2 shows a mode that was found to be unstable and hence representative of brake squeal.

Figure 2. Unstable brake squeal mode

Multidisciplinary optimization with MD Nastran offers a powerful design tool for brake squeal studies. The MD optimization feature allows engineers to develop designs which avoid problematic brake squeal frequencies. For example, the material characteristics of the brake system parts can be treated as design variables in MD optimization to overcome a specific brake squeal mode, thereby pushing the brake squeal phenomenon to a higher frequency. In the previous example, the weight of the caliper, disk, pads, and piston was treated as a design variable in an attempt to eliminate the unstable mode shown in Figure 2. The MD optimization solution identified a weight combination of these various brake system components that pushed the brake squeal mode in Figure 2 to a higher frequency, resulting in a new stable mode at the previous unstable brake squeal frequency. The new stable mode resulting from the MD optimization solution is shown in Figure 3.

MD solutions provide a complete brake squeal simulation environment, with vehicle motion analysis for brake system loading, nonlinear structural analysis for pad/rotor frictional contact, complex eigenvalue analysis for mode shapes and frequencies, and system level design optimization to arrive at desired brake squeal design conditions.
Conclusion

MD Nastran and MD Adams, the multidiscipline solutions from MSC.Software, provide a single, integrated platform for end-to-end brake squeal simulation.

With MD solutions, engineers can simulate the brake squeal performance of a complete braking system including motion, structural, non-linear, thermal, and vibration effects on the system. The traditionally separate analyses required for each of these disciplines are integrated under a common data model and common solver framework, avoiding the need for data transfer and translation between separate analyses and different solvers. MD optimization further increases the power of MD solutions for brake squeal, providing brake system component design optimization to develop brake systems which can avoid brake squeal at operating frequencies. Advanced solver technologies such as complex Lanczos eigenvalue extraction and parallelization enable scalable MD solutions for brake squeal on today’s popular hardware platforms.

With the power of MD Nastran and MD Adams, automotive manufacturers can reduce the need for costly physical testing while improving brake squeal characteristics with the many advantages of virtual testing. MD solutions provide the capability to study the effects of multiple disciplines under the same software environment with increased accuracy of simulation results, all while reducing the time and effort in the traditional brake squeal design process.