**EB2020-STP-037**

# COMPLEX EIGENVALUE ANALYSIS OF AUTOMOTIVE DISC BRAKE SQUEAL WITH AUTOMATION

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https://doi.org/10.46720/EB2020-STP-037

**ABSTRACT**: Brake Squeal is an important and challenging phenomena from an OEM's perspective, to avoid expensive warranty issues and provide squeal proof driving experience to its customers. It becomes critical to identify and take corrective measures in the initial design phase and to avoid multiple and expensive test on prototypes. Complex eigenvalue analysis (CEA) to predict the squeal frequencies is a well-established approach since last two decades. However, CEA has always been a domain for the experienced analyst, unexplored by the designers. In this study, an attempt has been made to automate complete CEA procedure, to evaluate brake squeal characteristics, which guides a novice designer to begin with a 3D CAD model and end up with the squeal propensity evaluation. Above procedure includes complete automation of brake model setup, including material properties, contact creation, boundary conditions and the result generation using a template-based definition. It also allows more robust and concrete evaluation of contact characteristics which is quintessential for mode coupling phenomena, that ultimately leads to brake squeal. Traditional techniques would take an experienced engineer, anywhere from few days to few weeks in performing CEA. Using this automation, the complete CEA analysis time can be reduced to just 3 to 4 hours, enabling designers to have deeper insights at a very early stage of brake design and development.

**KEY WORDS**: Brake Squeal, Complex Eigenvalue Analysis, Instability chart, Mode Coupling, Automation

## 1. Introduction

Over the years, brake squeal phenomenon has gathered a lot of attention especially to reduce the amount of driver discomfort and warranty costs for all the OEMs. The frequent occurrence of the squeal noise also creates an inflated perception of faulty braking system, leading to dissatisfaction among the rider community. This makes it critical to capture NVH (Noise, Vibrations and Harshness) characteristics of brakes with its potential impact. Different levels of noises from brakes are attributed to a wide range of frequencies generated from either squeal, groan, moan or judder phenomenon. In particular, hot judder vibration and squeal noise are non-linear coupled phenomena in automotive disc brake systems.[4]

Brake NVH problems have been recognized for a long time, however within the last 15-20 years special new disciplines have been developed allowing the introduction of technologies being mainly unknown to the majority of brake people such as FFT, Modal Analysis, Finite Element Analysis plus a large variety of high tech metrologies have added to the ability to solve NVH issues.[5]

Squeal simulation is an important step in a typical brake design development cycle. Selecting the right design and materials effectively and quantifying its effect on squeal demands extensive investigation. Therefore, optimizing the design for cost effective brakes require numerous squeal simulations to be completed in a shorter duration. Thus, through automation engineers can perform numerous complex and challenging simulations with very little effort, focussing more on delivering a low maintenance and highly efficient brakes.

Squeal occurs due to mode coupling behavior between the friction material i.e. brake pads and the rotor disc, in the form of instability arising from frictional forces. A typical squeal frequency occurs between 1kHz and 10kHz. Its occurrence and magnitude depends on multiple variables such as the contact pressure, friction between rotor disc and pads, material of disc, dimensions and material of pads etc. To study the effect of each of the above mentioned parameters it is very difficult, expensive and time consuming, to test even a single configuration of braking system on a brake dynamometer. Squeal phenomenon can be sensitive even to the least unexpected parameters such as the smallest geometric dimension.

Early insights on squeal characteristics give an edge to designers at the initial stage of the brake development cycle. A typical squeal simulation problem can be solved using two techniques, namely, Complex Eigenvalue Analysis and Dynamic Transient Analysis. In this paper, brake squeal prediction and the methodology developed is done using the former technique. Recent development of the Complex Eigenvalue Analysis (CEA) technique in finite element analysis has been a boon to engineers in quickly solving this challenging phenomenon. It is however critical to establish a good correlation between squeal results from simulation and experimental results.

Squeal analysis with CEA has been an experts technique for decades and brake designers have hardly used this technique until now. This paper shows an approach to democratize the brake squeal technique for designers through automation at an early stage in the design clycle.

## 2. Complex Eigenvalue Analysis in FEA

### 2.1. Introduction

Squeal simulation in FEA using Complex Eigenvalue Analysis (CEA) can be an effective technique in predicting squeal frequencies. The most preferred and accurate way to conduct a brake squeal is to perform a full nonlinear perturbed modal analysis. It consists of two stages i.e. to solve a nonlinear static analysis followed by a pre-stressed modal analysis. The nonlinear analysis captures the initial contact and also accounts for the sliding that occurs between pad and disc. The fluid pressure acting on piston, disc rotational velocity, press fit condition between the clips and pad, are a few that creates the pre-stress effect. The nonlinear frictional contact between pad and disc creates the asymmetric stiffness matrix. This friction coupling results in complex eigenvalues. The system is unstable if the real part of the complex eigenvalue is positive. Friction is one of the key factors that govern and dictate the mode coupling behavior, leading to squeal.

### 2.2. Finite Element Analysis

For any analysis it is imperative to begin with a clean 3D CAD geometry with the recommended pre-processing steps. It is critical to understand the appropriate key components in the analysis, identify its material properties, boundaries and loading conditions, before the analysis is begun. Any type of material and contact nonlinearity will make the analysis even more complex and challenging. Hence it is important to follow industrial and simulation best practices. The results from simulation provide unstable modes with a propensity level that highlights the possibility of the rate of occurrence for brake squeal. From the simulation results it is very much possible to miss the expected squeal mode at a particular frequency observed in an actual test. This could be due to in-correct material, boundary conditions, constantly changing friction between disc and pad etc. It has also been observed that a very small dimensional change on the pad alters or shifts the propensity of unstable modes. This emphasizes the importance of creating a master finite element model that needs to correlate well with available test data.

### 2.3. Master Model Generation

To create this master finite element model of the brake assembly automatically, a wizard has been developed inside ANSYS. It all begins with the import of 3D CAD model and the in-built intelligence in this tool identifies each component such as the caliper, disk, friction material, knuckle, piston, clips, torque member, bolts, etc and assigns appropriate material properties. It establishes right type of contacts between all relevant components and applies the boundary and loading conditions, as desired by the user.

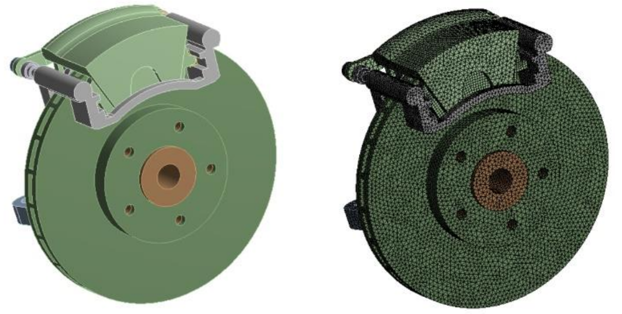


Figure 1- 3D CAD and Meshed Model

The advanced meshing capabilities in ANSYS are leveraged to the full extent resulting in the desired mesh which is a hybrid mesh of tetrahedral and hexahedral mesh. For certain components like the shim which are relatively very thin, special type of elements such as solidshell can be used which will be beneficial for the analysis. Automating this task is a key as performing this task manually on each component separately one by one, can be very time consuming too. Figure 1 illustrates the original 3D CAD model and its transformation to a fully meshed finite elment model, all done automatically.

### 2.4. Squeal Simulation setup

The nonlinear contact conditions, fluid braking pressure conditions along with the disc rotation needs to be solved for as prestressed conditions. The linear perturbation analysis technique is used to solve the above mentioned preloaded conditions. Newton Raphson technique is typically used while solving the nonlinear analysis. The tangent matrix from Newton Raphson analysis, can be used in the linear perturbation analysis to obtain the preloaded solution. This step is required to obtain a more accuration solution.

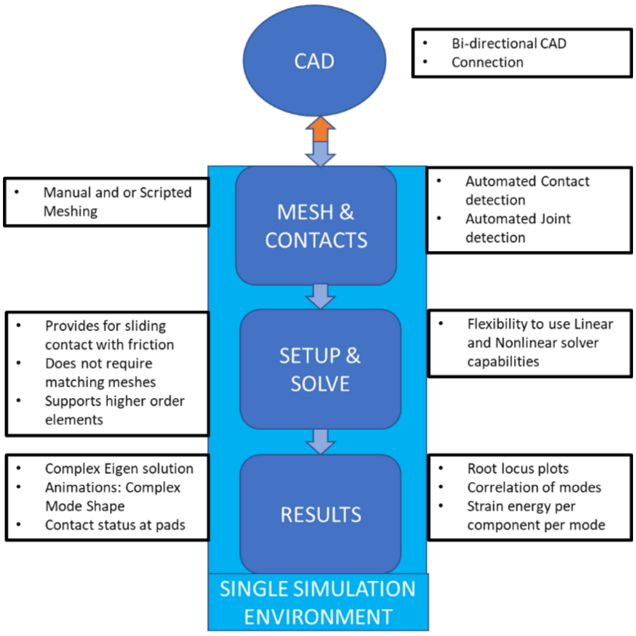


Figure 2- Squeal Simulation Workflow in ANSYS

The techniques used to solve for the disc rotation imparts a tangential sliding velocity at contact element nodes on the disc.

Linear perturbation analysis then generates the element stiffness matrices which are usually unsymmetric. The modal analysis then uses the unsymmetric matrix resulting in complex eigen frequencies.

The squeal simulation workflow proposed here from start to end, captures the required NVH characteristics of the brakes. The workflow can be adapted to meet any specific requirements. It highlights the procedure for a single simulation. However, the entire workflow, can be further refined to run multiple simulations all at the same time by leveraging a high performance computer grid. This gives an opportunity to evaluate the brake design configurations at a much faster rate. To investigate squeal characteristics it is essential to identify critical paramerters such as friction between pad and disc, Youngs modulus of the disc and pad. Geometric dimensions on the pad such as a hole diameter, change in the fillet radius at the corners, groves, cutout features etc. must also be evaluated. The proposed squeal simulation workflow is depicted in Figure 2.

## 2.5. Results

### 2.5.1 Reviewing Propensity Chart and Squeal Modes

After the simulation is complete the results include the instability chart or the propensity chart. The unstable modes at unstable frequencies are all generated in an automatic report as shown in Figure 3.

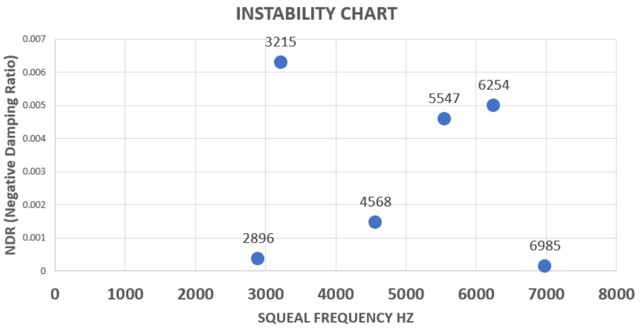


Figure 3 - Instability Chart and Unstable Mode Shapes

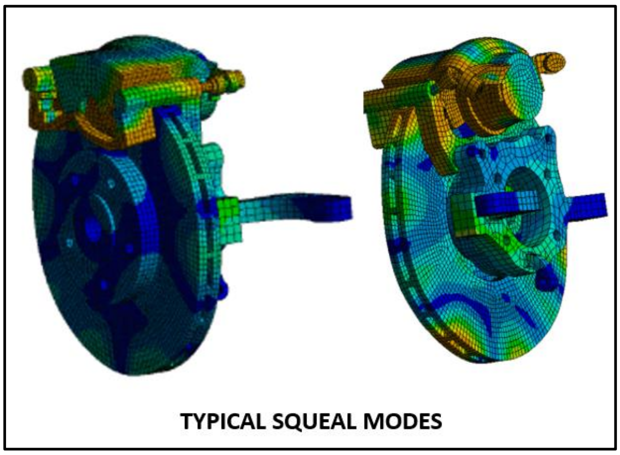
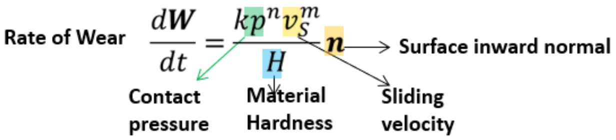


Figure 4 – Typical Brake Assembly Squeal Modes

The unstable modes are usually identified by the positive real part of the complex eigenvalue for the coupled modes. All the mode shapes generated from the squeal simulation can be studied closely to understand the mode coupling behavior as shown in Figure 4.

### 2.5.2 Capturing effect of wear on squeal behavior

A small amount of wear on the pad can have a big effect on the squeal characteristics. It is critical to study the change in the contact condition between the pad and disc, pad and the clips, caliper and pad, bolts and the torque member etc. during the pre-stress condition state. A natural consequence of the sliding contact is that both the rotor and the pads are wornout, affecting the useful life of the brake as well as its behavior.[3] Any user defined or an existing wear model, such as the Archard wear model can be used to capture varying pressure between the disc and the pad as shown in Figure 5.



$$\frac{dW}{dt} = \frac{kp^n v_S^m}{H}\mathbf{n}$$

Figure 5 – Archard Wear Model

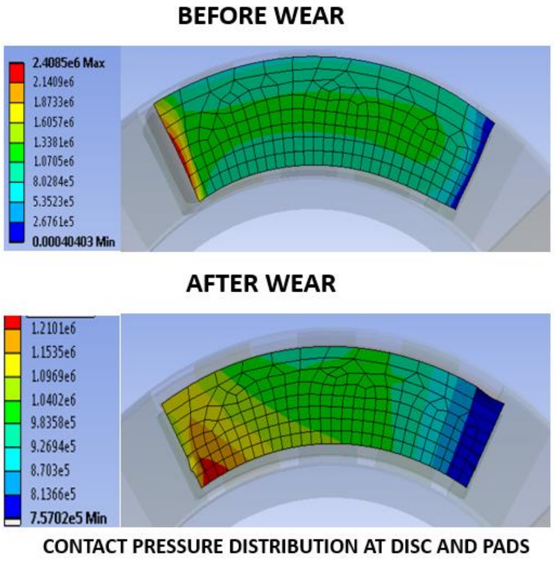


Figure 6 – Contact Pressure Distribution on Pads

The unavoidable variation on the thickness of pad can play a big role and is essential to account for, in a squeal simulation. It is evident from the results that the contact pressure is more distributed when wear is accounted for. Also, the mode coupling phenomena between pad and disc can be further explored by studying the varying contact pressure at the pads. Design changes on the pad can also be made after carefully evaluating contact pressure results. Variation in contact pressure, with and without wear, is illustrated in Figure 6.

### 2.5.3 Effect of Friction and damping on Squeal

The coefficient of friction is another important parameter to monitor in squeal analysis as it contributes to the mode coupling phenomenon. This dictates the need to do a parametric squeal simulation at multiple values of coefficient of friction. The effect of coefficient of friction can be clearly seen from the Root locus plots as shown in Figure 7.

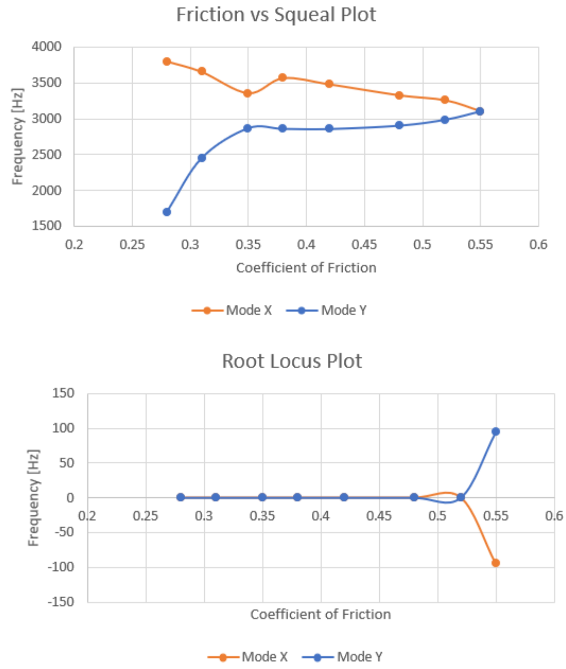


Figure 7 – Root Locus Plot and Mode Coupling

The friction induced mode coupling behaviour provides significant insight in the development cycle of brake design. The effect of squeal damping i.e. stabilizing and destabilizing damping can be critical and needs to be evaluated. From the dependencies of coefficient of friction on sliding velocity and contact pressure, the total variation of the potential energy[7] can be written as shown in Figure 8.

$$d\tau_i = t_i \underbrace{t_j c_d P \frac{\partial \mu}{\partial \|\dot{u}\|} d\dot{u}_j}_{\text{Negative/destabilizing damping}} + t_i \underbrace{\left(\delta_{ij} - t_i t_j\right) c_s \frac{\tau_{\lim}}{\|\dot{u}\|}}_{\text{Positive/stabilizing damping}} d\dot{u}_j$$

Figure 8 – Total Variation of Potential Energy

$\tau_i$ =Frictional stress

$t_i$ = Unit vector in the direction of slip ($i = 1, 2$)

$\|\dot{u}\|$ = Magnitude of current equivalent slip rate and $\dot{u}$ is prescribed rotation vector in CMROTATE command
$P$ = Contact pressure
$\tau_{\lim}$ = Limiting frictional stress = $\mu P$
$c_d, c_s$ = Destabilizing (FDMD) and stabilizing (FDMS) squeal damping factor to control the effects of damping

### 2.5.4 Effect of thermal heat on Squeal

The heat generated due to friction between disc and pad cannot be ignored for its role in altering the NVH characteristics. With the development of finite element technology the main way of studying the thermal structure of a disc brake is to simulate the temeprature field and the stress field.[10] As friction material is heated, its elastic modulus reduces and results in lowering of frequenices.[8] The change in the frequencies is caused by the consideration of thermal strain and due to it, the change of contact pressure between pad and disc.[9] The Figure 9 captures the temperature distribution on the rotating disc due to friction.

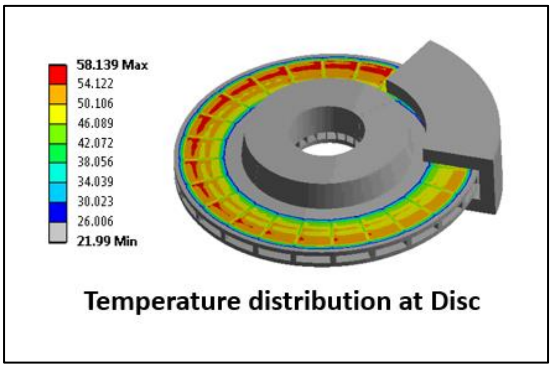


Figure 9 – Temperature Plot – Heat Generated due to Friction

As the braking sequence is more dynamic in nature, we cannot ignore factors that seem to be trivial yet has significant impact on squeal and mode coupling. One such factor is the surface stiffness, that varies due to surface irregularities on the pads. This can be derived experimentally and used as an input in the simulation. It is worthwhile to explore it further as an extension to the current study on CEA.

## 3. Conclusion

The complete automation presented here using the wizard in ANSYS for the squeal simulation provides the ultimate tool to designers and brake engineers. It not only reduces brake development design cycle but also helps to produce efficient and quiet brakes. It allows OEM's and brake suppliers to avoid huge maintenance costs with greater satisfaction to the driver community. Such a tool with a wide range of complexity can cater to the needs of a design engineer and an expert analysts, depending on their intent and level of expertise needed at different stages of the brake development cycle. The challenging task of optimizing the brake assembly components can be easily accomplished in this new user friendly environment. It gives an opportunity to correlate any available test data with simulation results and to explore and study multiple factors to reduce noise and any undesired squeal characteristics by taking swift and prompt measures accordingly. Such methodology can also be adopted to perform other brake phenomenons such as brake judder, moan and groan. The added benefit of such an automation is that it can also be applied to simulations not only in automotive but in non-automotive industries as well.

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## Acknowledgement

We would like to thank the Hyundai team for their support in this joint collaboration effort. We would also like to thank the ANSYS team including Sudesh Palase, Rahul Phadke and Ankur Jaura for successfully creating the wizard in ANSYS Mechanical to complement squeal simulation with automation.