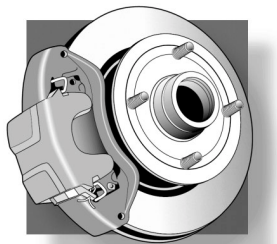


Introduction to Brake Noise & Vibration

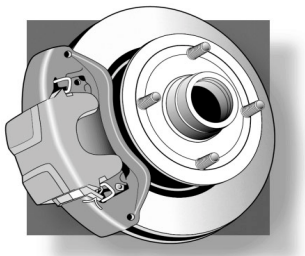
Weiming Liu & Jerome L. Pfeifer
Honeywell Friction Materials



Bendix
JURID

Presentation Outline

- Basic Noise Terminology
- Squeal
 - ≡ Definition
 - ≡ Contributing factors
 - ≡ Analysis tools
- Roughness and Groan
 - ≡ Definition
 - ≡ Contributing factors
 - ≡ Analysis tools
- Summary



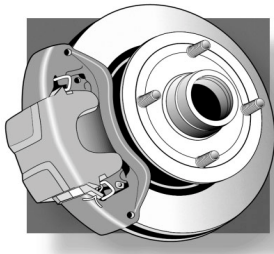
Introduction to Brake
Noise & Vibration

Basic Noise Terminology

- Sound - transmitted acoustic pressure waves (particle oscillation within an elastic media).
- Frequency - Rate of the acoustic wave repetition (cycles per second = Hz).
- Sound Pressure - Related to radiating surface area, surface vibration velocity, and distance from the source.
- Broad range in sound pressure necessitates the decibel (dB) notation.

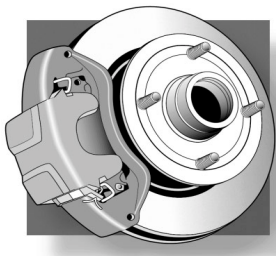
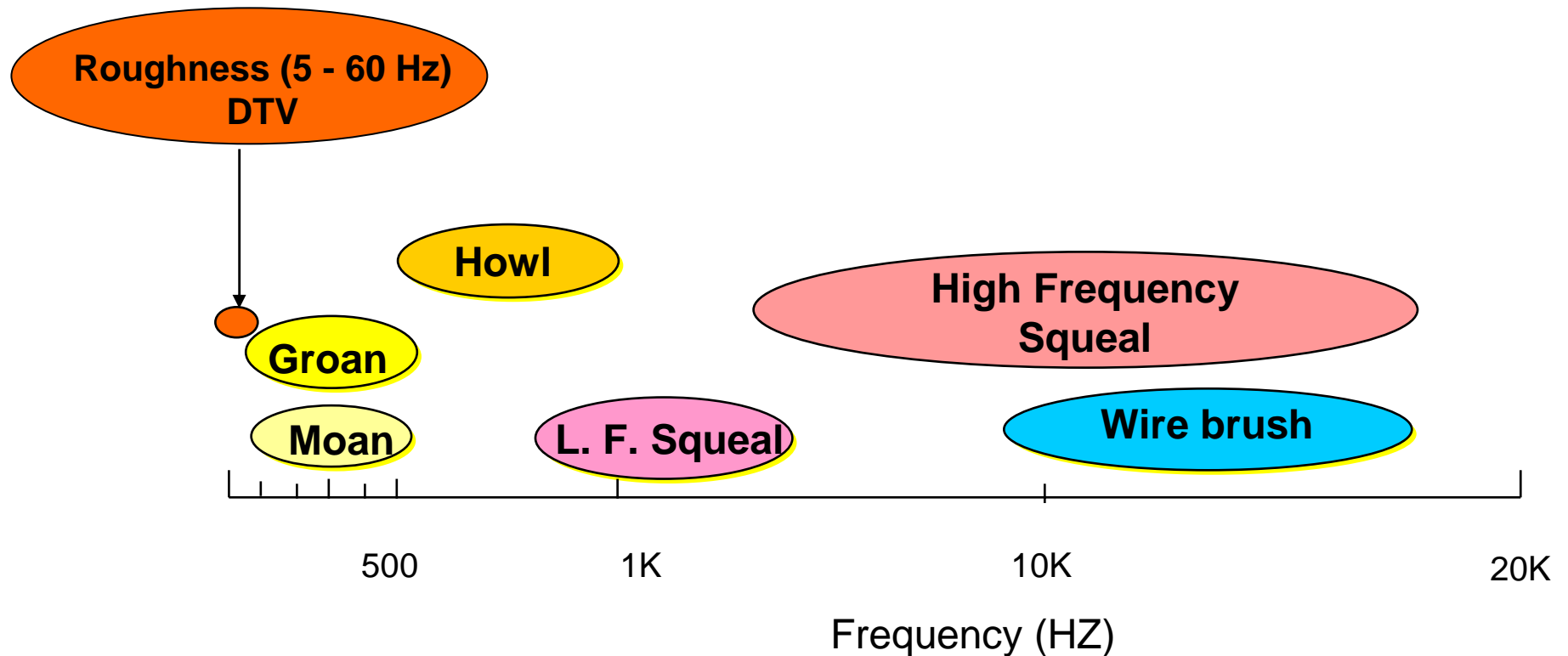
	Pascal	Decibel
Threshold of hearing	0.000021	0
Whisper (3 ft)	0.00021	20
Normal speech (3 ft)	0.021	60
Shouting (3 ft)	0.21	80
Auto horn (5 ft)	0.21	80
Chipping hammer (3 ft)	2.1	100
75 piece orchestra	21	120
Medium jet engine (10 ft)	2100	160

Receiver	Frequency (Hz)
Human	20 ~ 20000
Dog	15 ~ 50000
Cat	60 ~ 65000
Bat	1000 ~ 120000
Cricket	100 ~ 15000
Robin	250 ~ 21000
Porpoise	150 ~ 150000



Introduction to Brake
Noise & Vibration

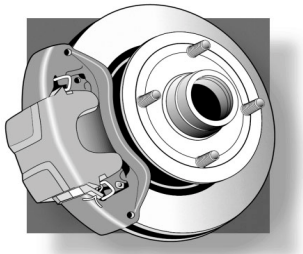
Frequency Range for Brake Noise and Vibration Issues



Introduction to Brake
Noise & Vibration

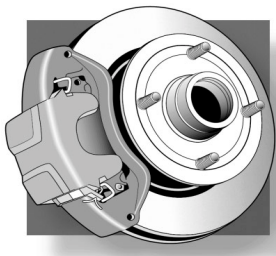
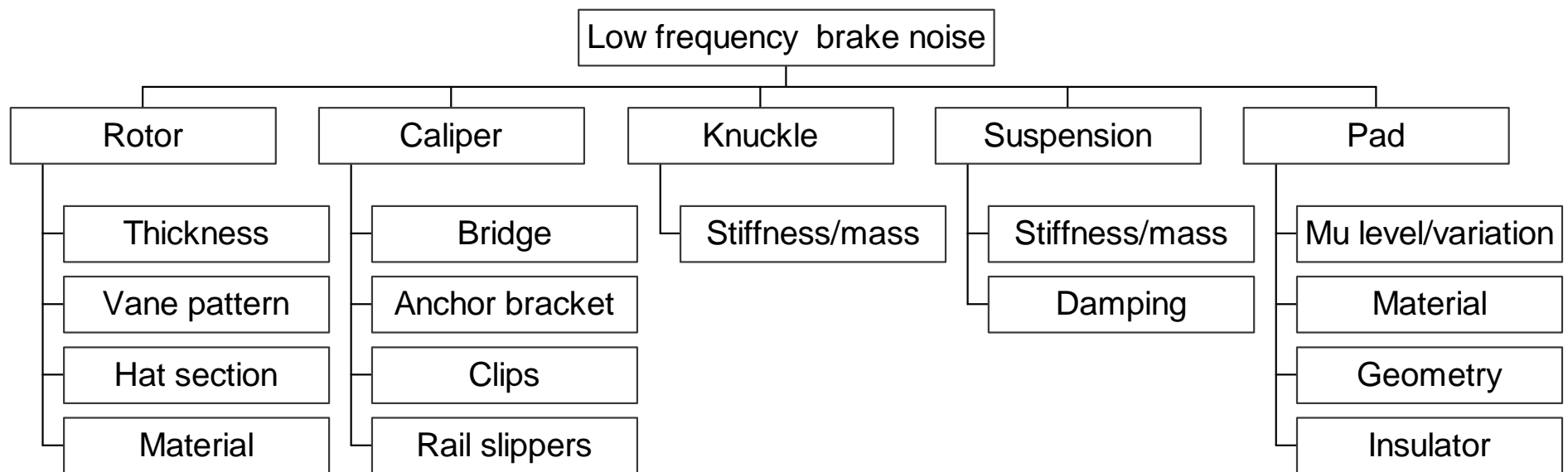
Brake Squeal

- Brake squeal is a phenomenon of dynamic instability that occurs at one or more of the natural frequencies of the brake system.
- The excitation comes from the friction couple.
- The disc rotor is acting like a “speaker” (sound wave radiated from the rotor surfaces).
- Pads and rotor coupling has major impact on mid to high frequency (4 ~ 16 kHz) squeal.
- Low frequency (1 ~ 3 kHz) squeal typically involves caliper, anchor bracket, knuckle and suspension, in addition to pads and rotor.



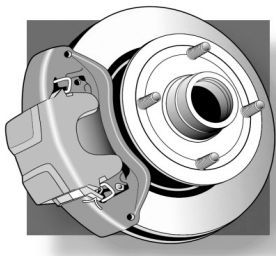
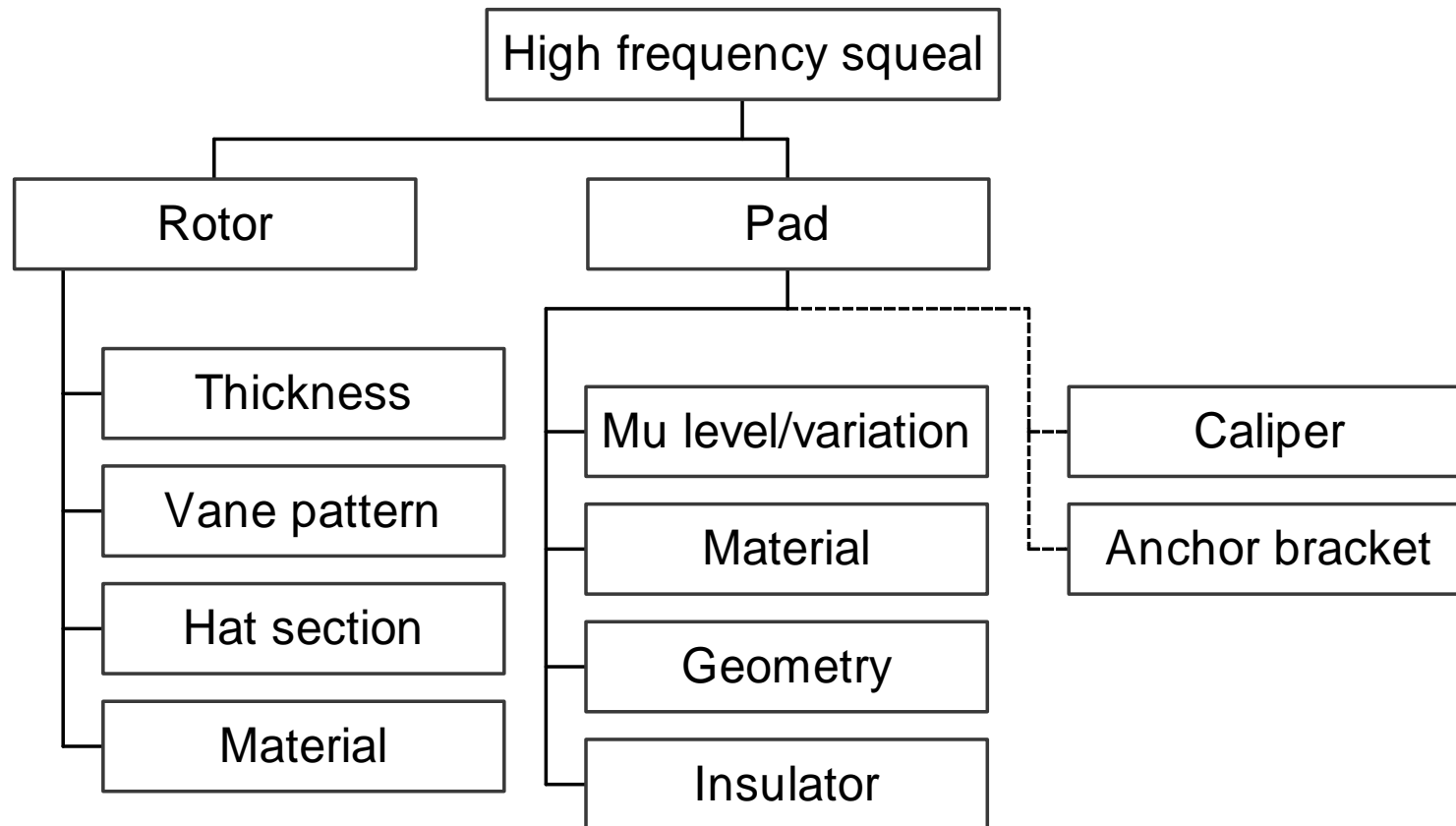
Introduction to Brake
Noise & Vibration

Factors Influencing Low Frequency Brake Noise



Introduction to Brake
Noise & Vibration

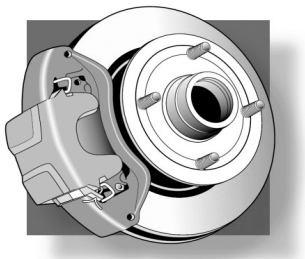
Factors Influencing High Frequency Brake Noise



Introduction to Brake
Noise & Vibration

Tool Box for Brake Squeal

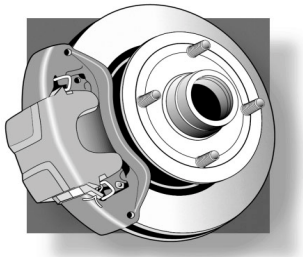
- Investigation, analysis, and validation tools:
 - ≡ Vehicle test
 - ≡ Dynamometer test
 - ≡ Modal test
 - ≡ Finite element simulation
- Common solutions:
 - ≡ Reduce excitation (chamfer design)
 - ≡ Increase damping (insulator selection)
 - ≡ Shift component natural frequencies (rotor, shoe plate, caliper and anchor bracket modification)



Introduction to Brake
Noise & Vibration

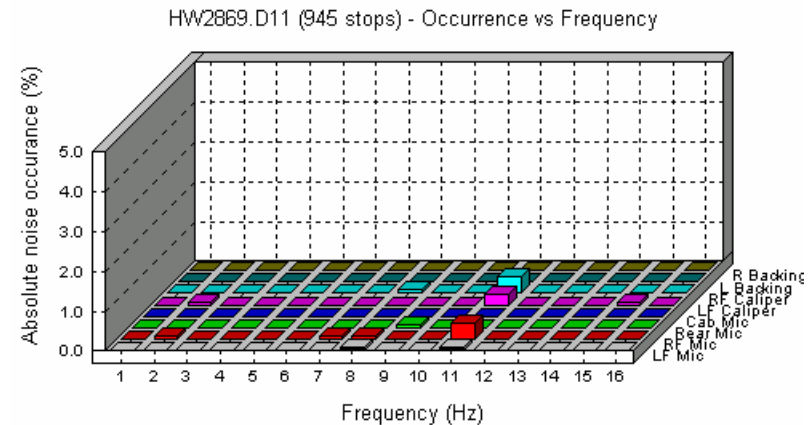
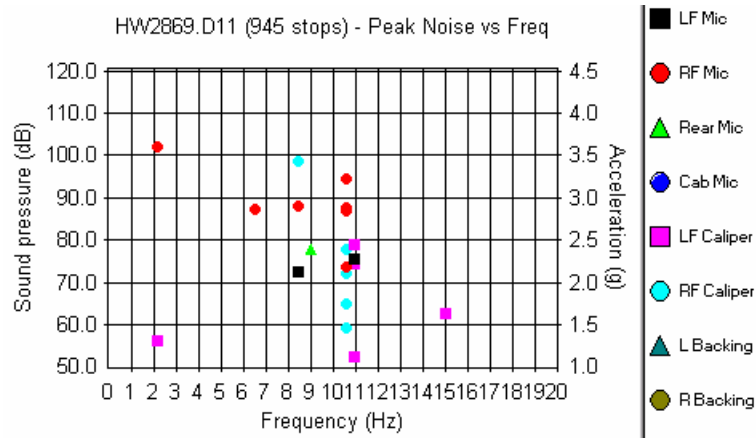
Vehicle Test

- The ultimate judge for successful noise solutions.
- Test procedures (North America):
 - ≡ Los Angeles City Traffic (LACT) - Standard brake noise and wear validation test; Different routes for each OE
 - ≡ Detroit Suburban Traffic (DST) - Mainly for DTV
 - ≡ Other tests from different OEMs and suppliers - For noise investigation and quick validation
- Driver's noise ratings, noise counts, sound pressure and/or acceleration data are collected throughout the test.

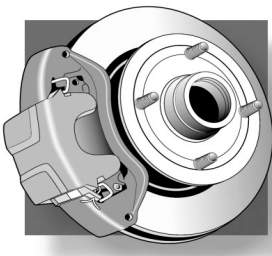


Introduction to Brake
Noise & Vibration

Typical LACT Noise Results



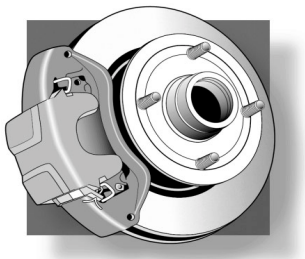
- Squeal events are identified from FFT spectrum.
- The number of noise occurrences and amplitudes are summarized.
- Additional calculations may be requested by customers.



Introduction to Brake
Noise & Vibration

Dynamometer Test

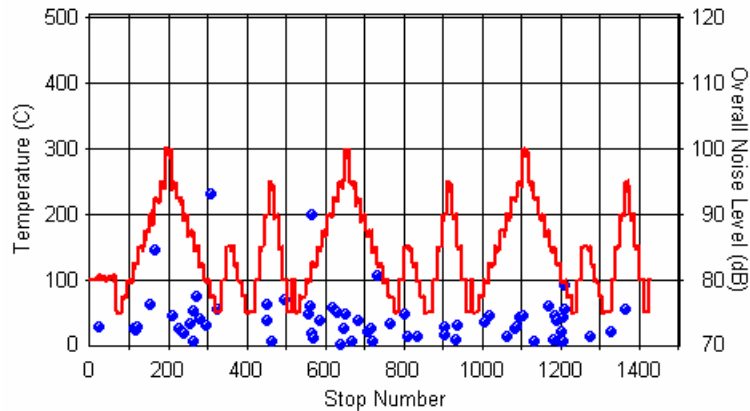
- Provides noise validation within a controlled environment.
- Lower cost and quicker to run than vehicle test.
- Test procedures:
 - ⌘ SAE J2521 - Developed after AK with the addition of inertia stops
 - ⌘ AK - European originated procedure (mainly drag stops)
 - ⌘ Simulated LACT - A series of stops similar to LACT driving conditions
 - ⌘ The combination of the above
- Sound pressure data are typically collected throughout the test.



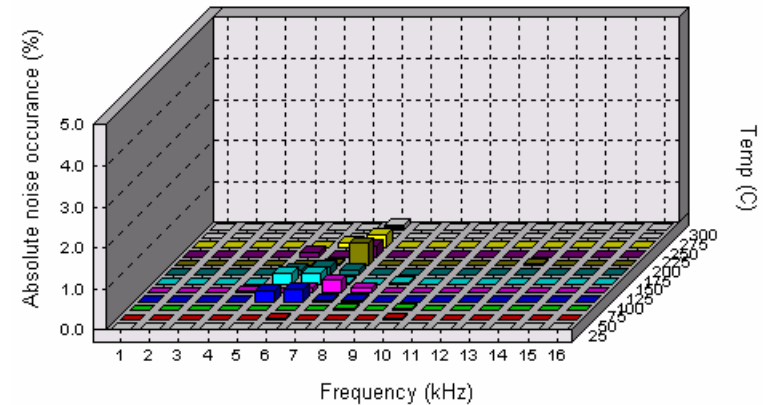
Introduction to Brake
Noise & Vibration

Typical Dynamometer Test Results

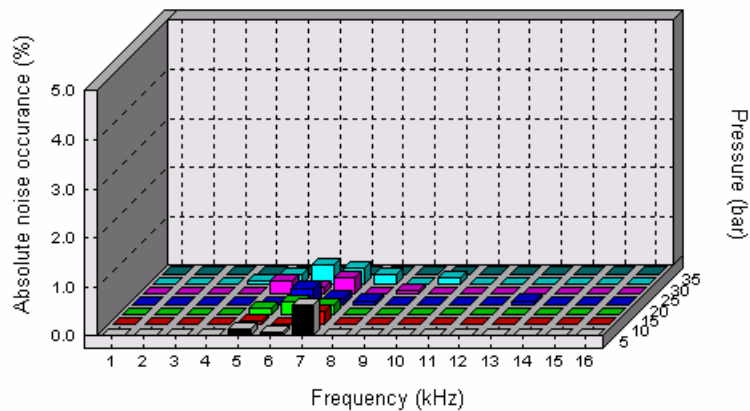
a187_20 - Temp and OA dB level vs Stop



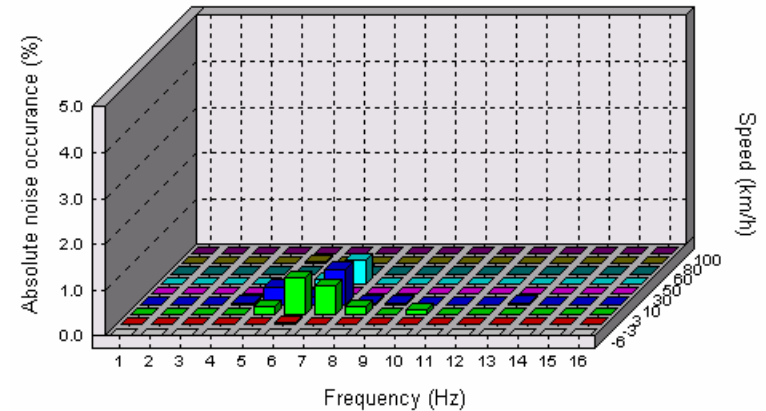
a187_20 - Noise occurrence vs frequency & temp (Total = 4.7%)



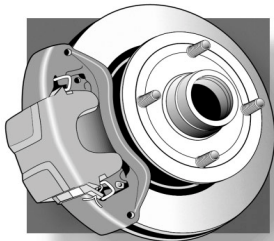
a187_20 - Noise occurrence vs frequency & pressure (Total = 4.7%)



a187_20 - Noise occurrence vs frequency & speed (Total = 4.7%)



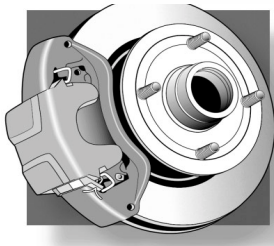
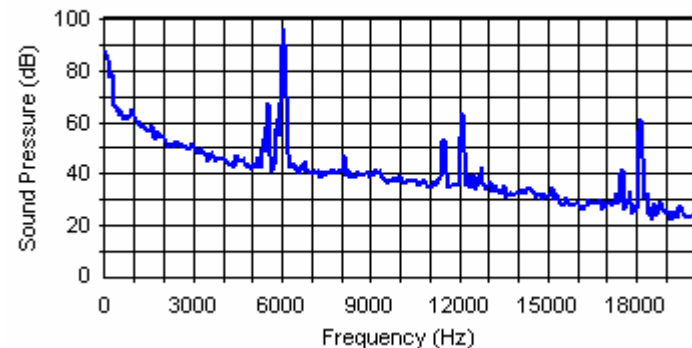
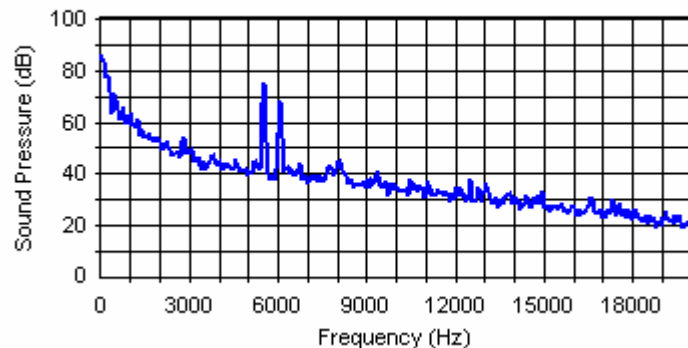
Noise occurrence over frequency, temperature, pressure, and speed range can be identified.



Introduction to Brake
Noise & Vibration

Identification of Squeal Events

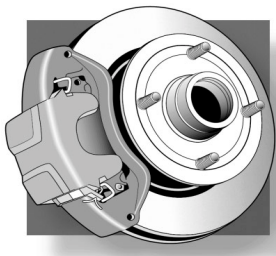
- Brake squeal can be identified and classified subjectively (by drivers) or objectively (processing microphone and accelerometer data).
- Not every up and down on the FFT spectrum curve can be considered as a squeal event.
- Brake squeal has a distinctive peak with possible harmonics displayed in its FFT spectrum.



Introduction to Brake
Noise & Vibration

Repeatability and Reproducibility of Brake NVH Testing

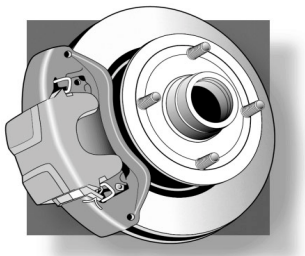
- The underlining mechanisms of brake squeal involve multiple aspects in the brake system. It is not uncommon to face the following problems:
 - ⌘ Correlation between vehicle and dynamometer tests
 - ⌘ Repeatability and reproducibility between vehicles or dynamometers
- Correlation is more difficult to achieve for low frequency squeal since more components come into play.
- Environmental factors such as weather, ambient temperature, humidity and road dust may also influence test results.
- Best practices to improve repeatability and reproducibility in brake NVH testing:
 - ⌘ Use the correct level of hardware
 - ⌘ Set the correct test parameters
 - ⌘ Ensure consistency of test parts
 - ⌘ Document all variations and significant events during the test
 - ⌘ Properly collect and analyze data



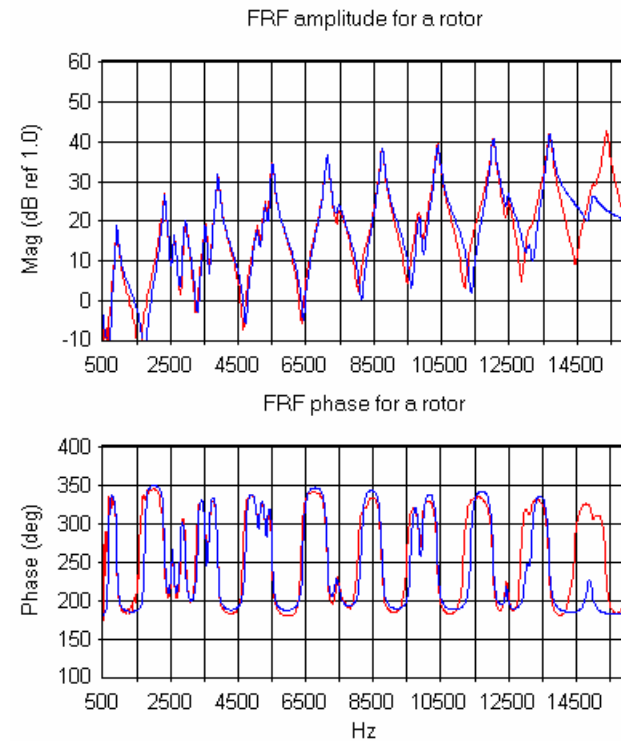
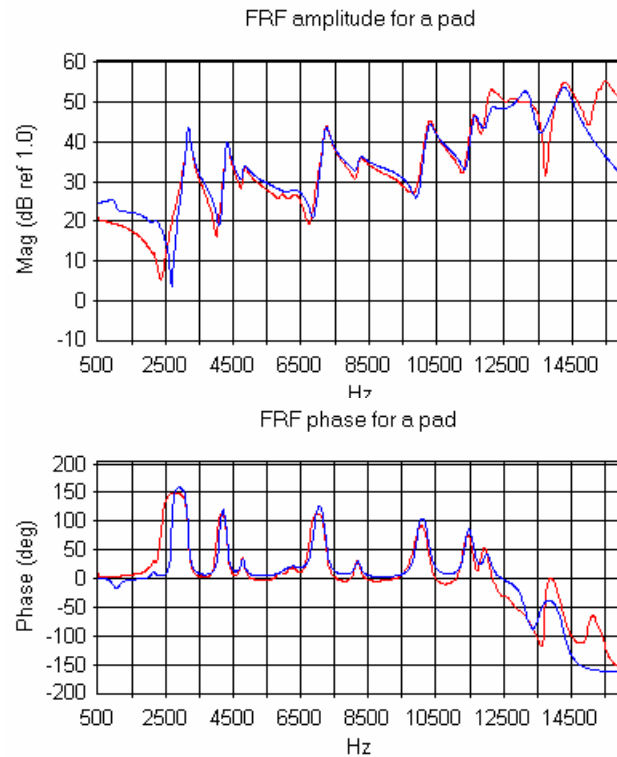
Introduction to Brake
Noise & Vibration

Modal Test

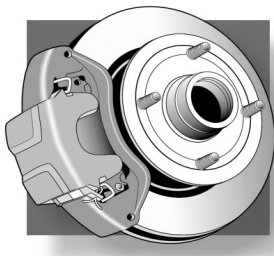
- Provides understanding of structural dynamic characteristics of the components and brake system.
- Component modal test measures natural frequencies, modal damping ratios, and/or mode shapes of pad, rotor, insulator, caliper, anchor bracket, knuckle, etc.
- System modal test is conducted on brake system on vehicle or dynamometer.
- Impact Hammer Test - quick and inexpensive.
- Laser Vibrometer - more elaborate with expensive equipment.
 - ≡ Mode shape determination
 - ≡ Operating deflection shape (ODS) measurement



Typical Modal Test Results



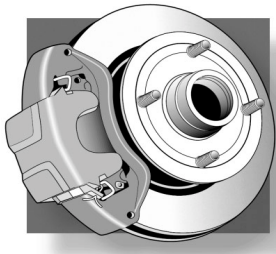
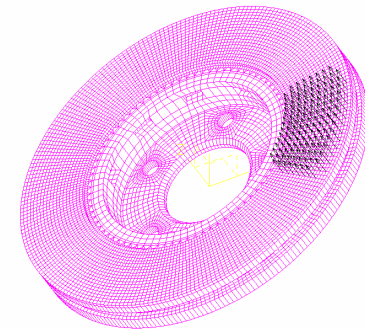
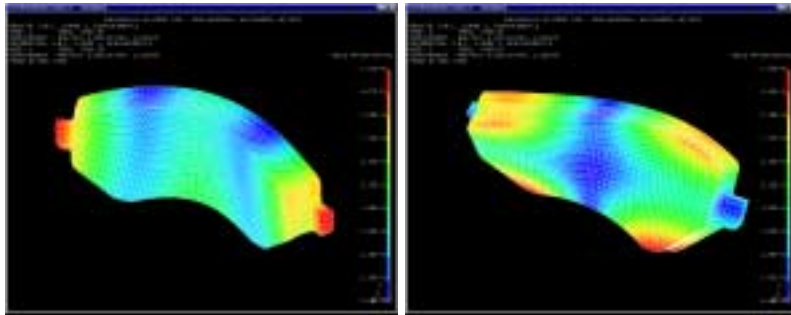
- Natural frequencies and modal damping ratios may be estimated from measured frequency response (=acceleration/force) curves.
- The actual squeal frequency may differ from individual component frequency because of system coupling effect.



Introduction to Brake
Noise & Vibration

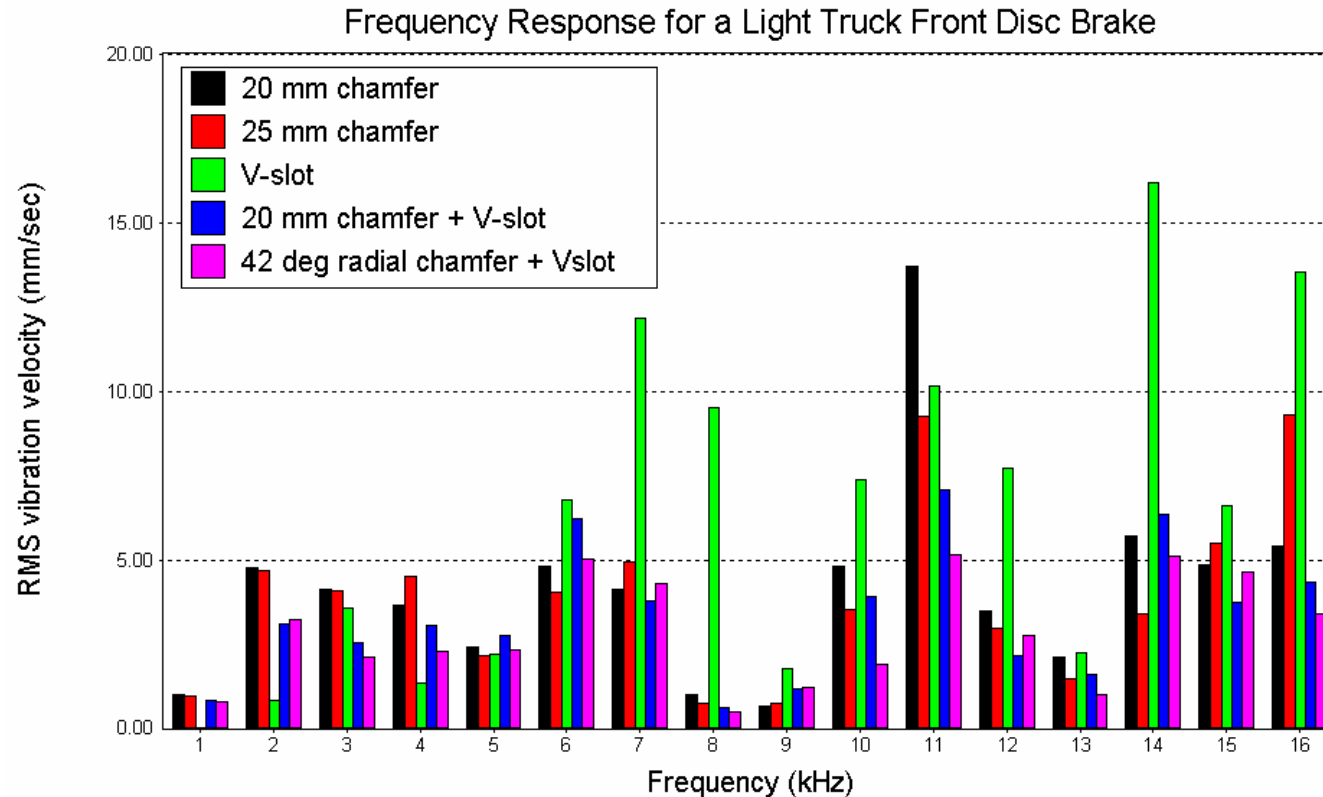
Finite Element Simulation

- Enabling multiple design iterations to optimize noise performance without building prototype parts and tests.
- Two types of models:
 - ≡ Brake system instability model (complex eigenvalue analysis)
 - includes all major corner components
 - suitable for low to mid frequency squeal
 - ≡ Pad-rotor-caliper support model (frequency response analysis)
 - includes pads and rotor with simulated caliper-anchor bracket supports
 - suitable for mid to high frequency squeal

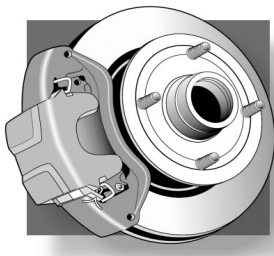


Introduction to Brake
Noise & Vibration

Pad Shape Optimization Through FE Simulation



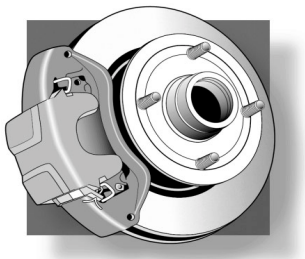
- Different pad shape, shoe plate thickness, and rotor geometry can be quickly evaluated.
- An optimized configuration may be chosen without any vehicle or dyno testing.



Introduction to Brake
Noise & Vibration

Brake Roughness Definition

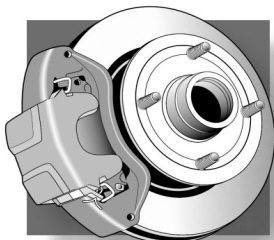
- Brake Roughness is the vehicle vibration, jerkiness, or pulsation that is felt by the driver and or passenger:
 - ≡ During a braking stop
 - ≡ Sensed through
 - steering wheel (shake or nibble)
 - floor boards or dash panel
 - car seat
 - brake pedal
 - ≡ Created by repetitive variation in torque output from the brake
 - typically in the 5-60hz range
 - frequency varies with wheel speed
 - typically 1 to 2 pulsations per revolution but can reach up to 10



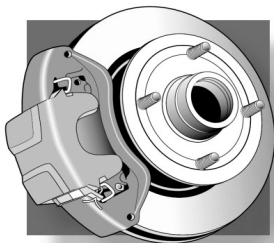
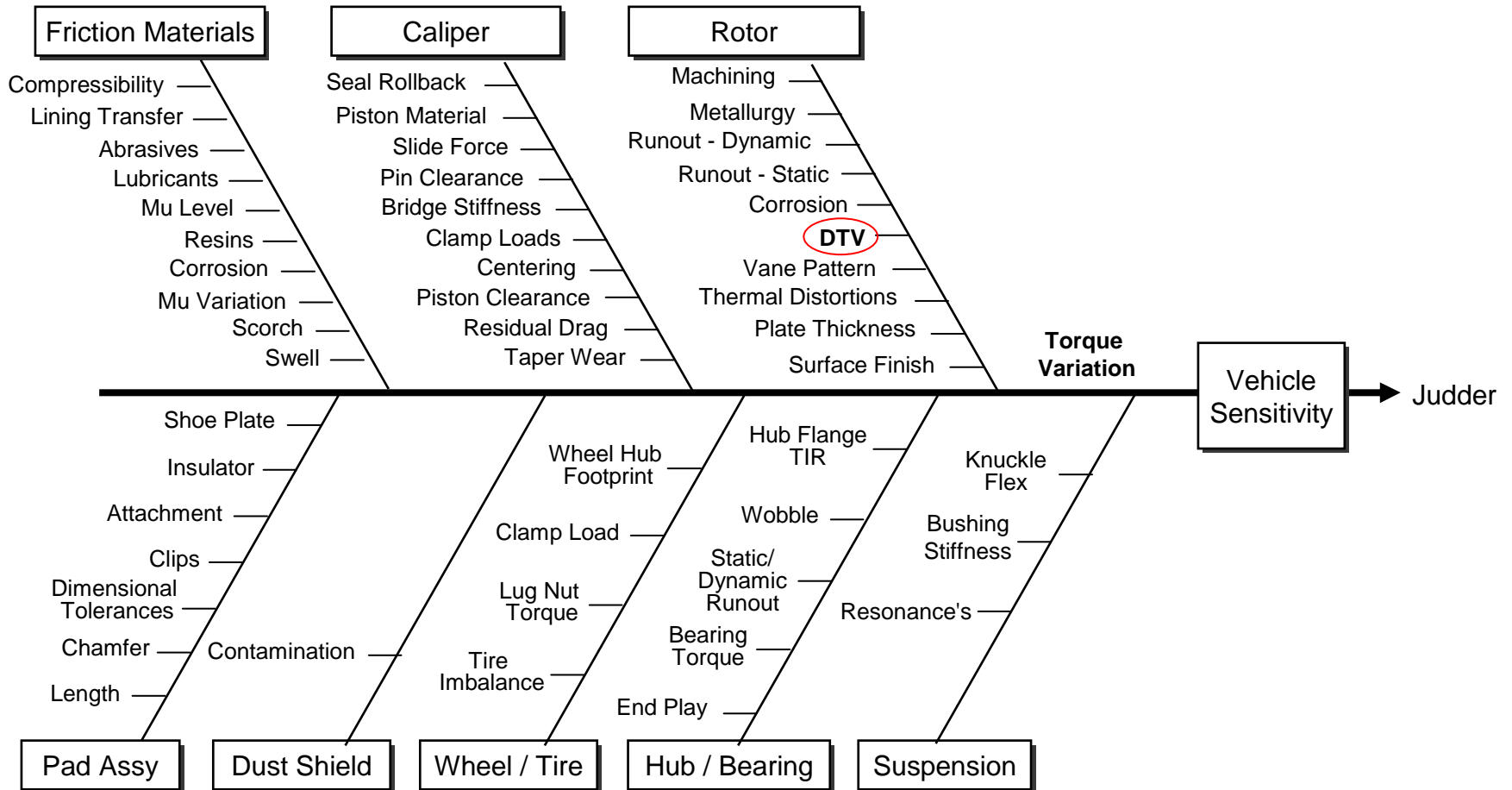
Introduction to Brake
Noise & Vibration

Brake Roughness Definition (Cont'd)

- Severity of roughness dependent on:
 - ≡ Magnitude & Frequency of the brake torque variation
 - ≡ Sensitivity of the vehicle
 - transmission path through suspension & steering components
 - resonance frequency & damping of vehicle components
- Brake Roughness, also commonly called Judder or Shudder, is often tagged with a descriptor that helps define the conditions where the roughness is noticed:
 - ≡ Hot Judder, Brake temperature $> 200\text{ }^{\circ}\text{C}$
 - ≡ Cold Judder, Brake temperature $< 100\text{ }^{\circ}\text{C}$
 - ≡ Green Roughness, New brake
 - ≡ Wet Roughness, Water soaked
 - ≡ High Speed Judder, $> 130\text{ kph}$



Possible Contributors to Roughness



Introduction to Brake
Noise & Vibration

Brake Torque Variation

$$\text{Torque} = F_f * r = 2u * F_N * r = 2u * P * A * r = c * u * P * r$$

Let's look at what parameters could vary and contribute to torque variation

$$dT = c * u * r * dP + c * r * P * du + c * u * P * dr$$

Although all three have been observed to cause torque variation, the most serious is from brake pressure fluctuation

dP mainly caused by Rotor Thickness Variation (RTV)

F_f = braking force

r = effective radius of brake

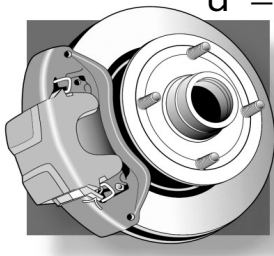
u = coefficient of friction

F_N = force exerted by caliper on pad

P = brake line pressure

A = caliper piston surface area

$c = 2A$



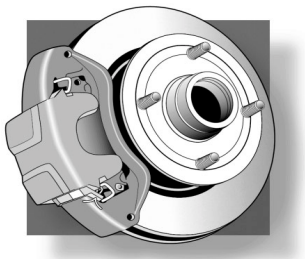
Introduction to Brake
Noise & Vibration

Contributors to Rotor Thickness Variation

- Lining Transfer
- Thermally Induced Distortions / Growth
- Corrosion
- Uneven Wear Patterns from Off-Braking / On-Braking Drag

Uneven rotor wear caused by varying pad contact while driving at highway speed is the factor that usually has the most significant influence on creating brake roughness. There can be selective wear on either one side of the rotor, or on both sides of the rotor.

Rotor Thickness Variation in the range of 15-20 μm (or about half the thickness of a human hair) can create torque variation in the range of 50 NM. This normally is sufficient to create vehicle roughness issues.



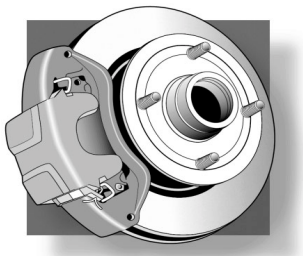
Introduction to Brake
Noise & Vibration

Factors Influencing Uneven Wear During Off-braking and On-braking Driving

- Mounted **Runout** of the rotor (bearings, machining, lug nut forces) IDEAL = 0
- Caliper **Clearance** (seal rollback, slide forces, bridge / finger stiffness) IDEAL = High
- **Aggressiveness** of the friction material and pad dimensions IDEAL = Low
- Load Deformation of knuckle and caliper bracket IDEAL = 0

Have to consider other brake system requirements such as pedal feel, rotor rust removal, rattle, wheel dust generation, etc.

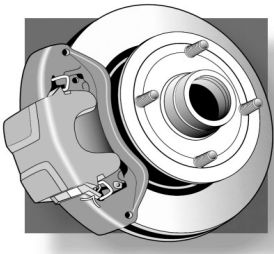
A recommended approach to minimize roughness is to look at the entire brake corner as an interactive system and address all these interactions instead of concentrating on only one component.



Introduction to Brake
Noise & Vibration

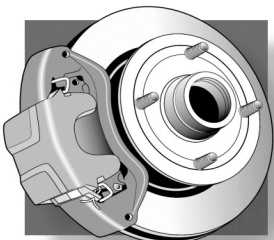
Groan Definition

- Groan is a low frequency noise that is more distinctly heard inside the vehicle than outside the vehicle:
 - ≡ Emanates from body structure in response to vibrations/pulsations created in brake
 - ≡ Frequency typically in range of 30 - 600 hz
 - ≡ Frequency content usually controlled by resonance modes in body and suspension system components
 - ≡ Frequency sometimes driven by higher order of wheel rotational speed
- Dynamic Groan:
 - ≡ Created during a brake stop
 - ≡ More pronounced from middle to end of stop
 - ≡ Often requires prior thermal conditioning stops and or more aggressive stops to bring out the groan



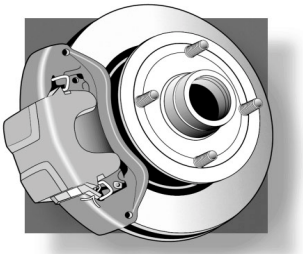
Groan Definition (cont'd)

- Creep Groan:
 - ⌘ Created when vehicle starts inching forward under light brake pressure
 - ⌘ Occurs within narrow brake pressure / speed window
 - ~ 0.2 - 2 rpm
 - ~ 30 - 70 psi
 - ⌘ Brake restraining the torque from automatic transmission
 - ⌘ Noise signature usually made up of a string of pulsations (~ 3 - 10 per sec)
 - ⌘ Pulsations attributed to slip-stick event between pad/caliper assembly & rotor
- End of Stop Crunch / Grunt / Release Grunt:
 - ⌘ Terms to describe noise heard at end of stop as vehicle recovers from nose dive or when brake pressure released and suspension windup relaxes



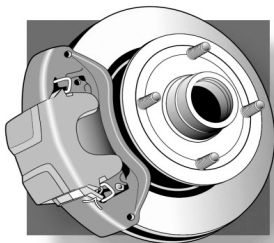
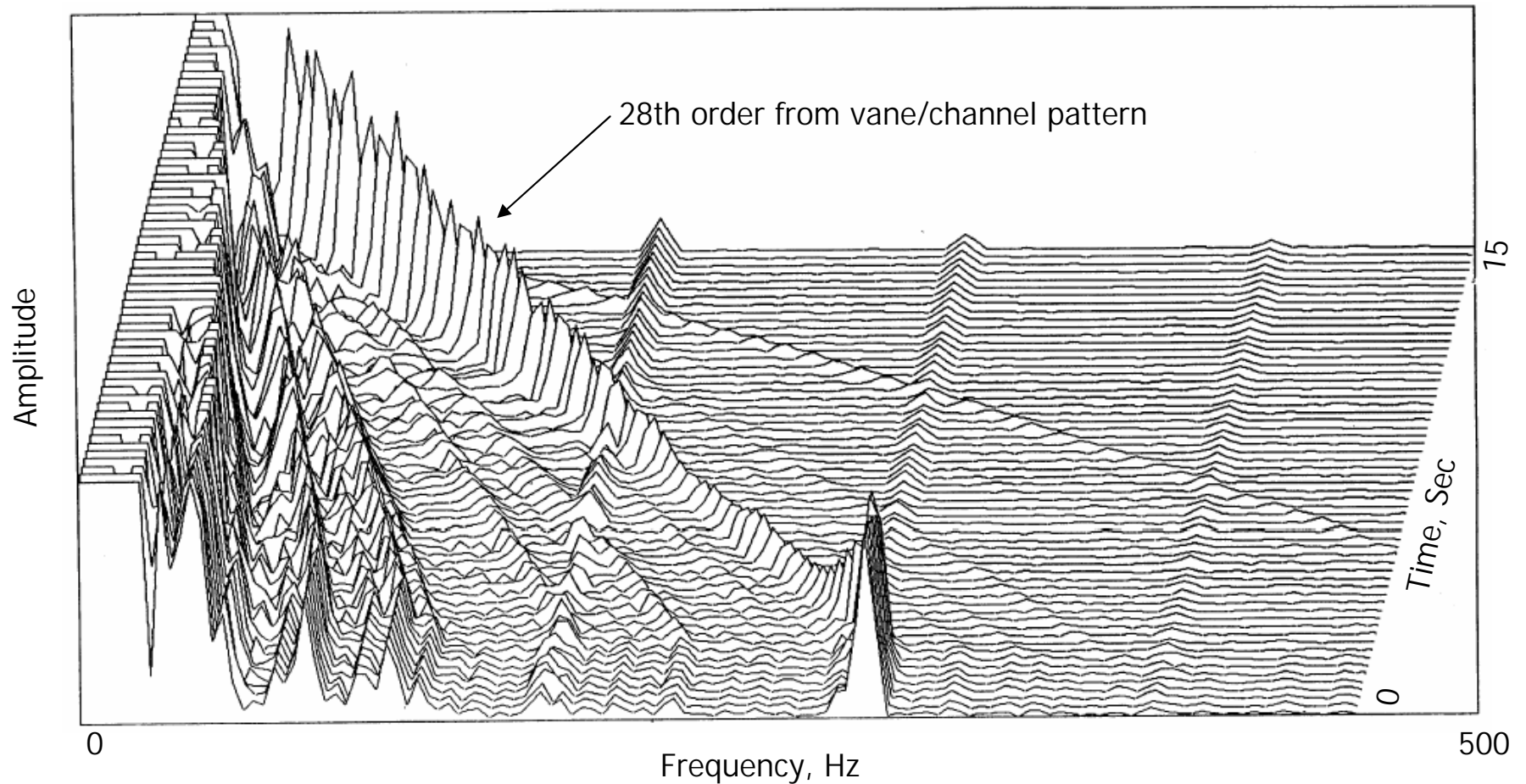
Potential Contributors to Groan

- Rotor Deformations - vane/channel surface ripples, grind/swirl surface finish patterns, etc.
- Pad thermal deformation
- Pad load pattern
- Friction film on rotor, μ variation
- Pad physical property values, shear and compression
- μ versus speed, static / dynamic
- Caliper stiffness
- Bushing stiffness
- Etc.



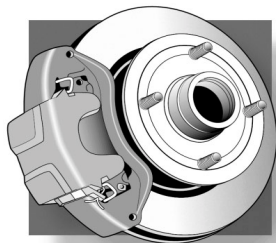
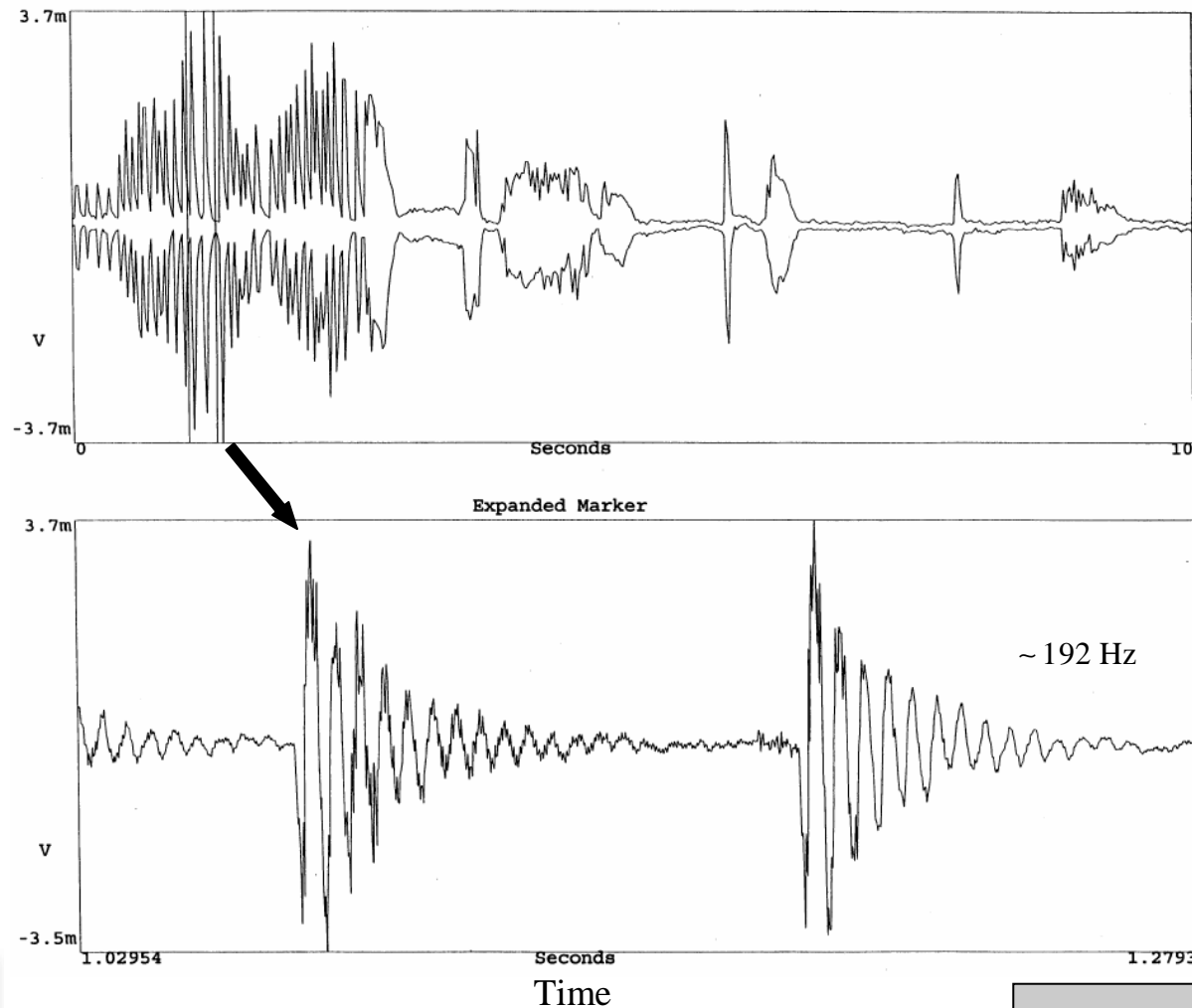
Introduction to Brake
Noise & Vibration

Dynamic Measurement of Instop Rotor Thickness Variation Showing How Vane Channel Surface Ripples Can Contribute to Groan



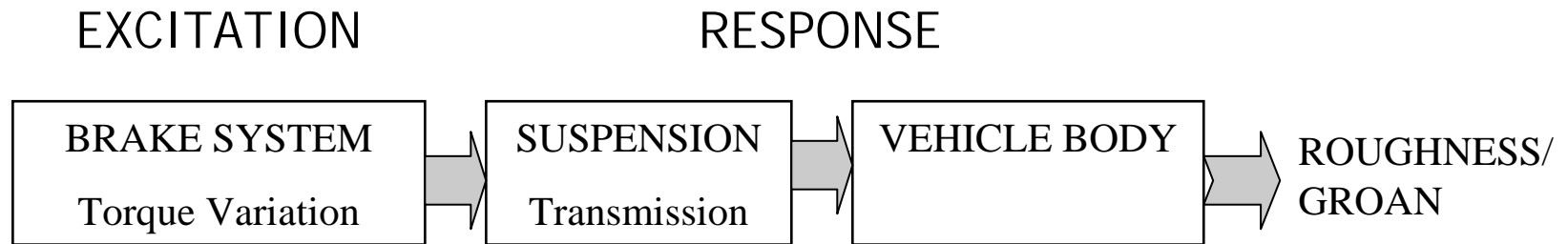
Introduction to Brake
Noise & Vibration

Signature of Creep Groan Vibration Taken With Accelerometer Mounted on Vehicle Suspension

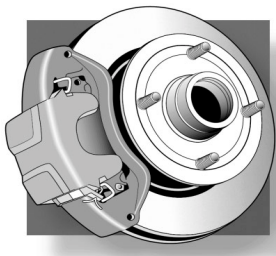


Introduction to Brake
Noise & Vibration

To Reduce Roughness or Groan



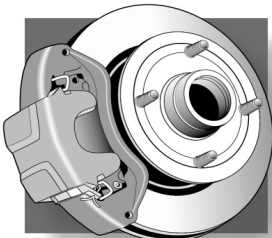
- Minimize excitation mechanism in brake
- Minimize vehicle response
 - ≡ Increase Isolation / Damping in Suspension
 - ≡ Add Damping to body components
 - ≡ Shift Resonant Frequency of vehicle component



Introduction to Brake
Noise & Vibration

Methods for Evaluating Roughness/groan Issues

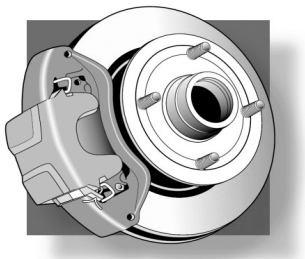
- Vehicle tests (subjective driver ratings, with some accelerometer, torque wheel, strain gage, and microphone signature analysis)
 - ≡ LACT
 - ≡ DST
 - ≡ Laurel Mountain
 - ≡ Western ride
 - ≡ Eastern Mountain ride
 - ≡ Specialized procedures
- Lab tests (quantitative comparisons, but difficult to duplicate vehicle conditions in lab setting)
 - ≡ Off-Braking / On-Braking DTV procedures
 - ≡ Rotor / friction sample low pressure wear
 - ≡ Dyno wear tests, bath tub
 - ≡ Static / Dynamic mu measurements
 - ≡ In-stop torque variation and rotor thickness variation measurements



Introduction to Brake
Noise & Vibration

Summary

- Brake noise and vibration issues arise from a complex interaction between the various brake and suspension components.
- Successful and more robust solutions come from:
 - ≡ Understanding the system and individual components
 - ≡ Systems approach
 - ≡ Utilization of proper tools for given problem
 - ≡ Careful interpretation of test and simulation results
- Need to continue progress made on enhancing lab and vehicle test procedures, data collection and analysis, as well as modeling tools.



Introduction to Brake
Noise & Vibration