SURFACE VEHICLE RECOMMENDED PRACTICE

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(R) Verification of Brake Rotor and Drum Modal Frequencies

RATIONALE

This revision includes updates and additions to accommodate laboratory rotor and drum modal analysis, which is very useful in the design/development phase of an automotive brake system.

TABLE OF CONTENTS

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1. SCOPE

This document describes standard test methods, analysis methods, and reporting methods for measuring the resonant modes of automotive disc brake rotors and drums for design/development and production verification of these components.

1.1 Purpose

Part A of this procedure may be used during the design and development phase to determine the resonant frequencies and mode shapes of the brake rotor or drum. Part B of this procedure may be used for verification of the production capability of a plant to produce brake rotors or drums that are consistent with the production part approval process (PPAP). The procedure may be used to fingerprint parts used for the design validation process.

2. REFERENCES

2.1 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

Abdelhamid, M. and Denys, E., "Brake Rotor Modal Frequencies: Measurement and Control," SAE Technical Paper 2010-01-1688, 2010, https://doi.org/10.4271/2010-01-1688.

2.1.2 Other Publications

Kraus, T., and Abdelhamid, M.K., "Detection of IP and OP modes of vented rotors with fiber laser modal analysis," Bosh Technical Report.

Lee, H. and Singh, R., "Acoustic radiation from out-of-plane modes of an annular disk using thin and thick plate theories."

Yang, M., Afaneh, A-H., and Blaschke, P., "A study of disc brake high frequency squeals and disc in-plane/out-of-plane modes."

3. DEFINITIONS

3.1 FREQUENCY RESPONSE FUNCTION (FRF)

In simple terms, an FRF describes the magnitude and phase of the test structure dynamic response as normalized by the exciting force. An FRF measurement consists of measuring the excitation force, using a force transducer, and the response, typically by using a motion transducer (displacement, velocity, or acceleration). Other physical measurements, such as sound pressure or air particle velocity may also be used.

3.2 ACQUISITION TIME

The acquisition time is the total time required to collect a measurement. Denoted as T, it is equal to the block size (the number of samples acquired), multiplied by Δt (the time between samples).

3.3 SPECTRAL LINES

Spectral lines are the maximum number of spectral frequency lines. It is equal to the number of time samples divided by 2.56.

3.4 BANDWIDTH

The bandwidth is limited by maximum frequency (Hz) measured. According to the Nyquist sampling theorem, the maximum frequency is equal to 1/2 the sampling frequency. Most front-ends are equipped with their anti-aliasing filter (typically 3 dB per octave) at 80% of the bandwidth. Above 80% of the bandwidth, errors in amplitude and phase can be expected. Therefore, data within the high range of the bandwidth should be used with caution.

3.5 FREQUENCY RESOLUTION

The frequency resolution is the frequency difference (Δf) between spectral lines. Δf is equal to the bandwidth divided by spectral lines. When Fast Fourier Transform (FFT) is used to calculate the FRF, Δf is also the inverse of acquisition time.

4. PROCEDURE

4.1 Preparation - Part A - Rotor Modal Analysis

4.1.1 Setup: Free-Free Condition

Free-free condition is the rotor support condition intended for this procedure. The actual support method used needs to simulate free-free conditions as closely as possible. Validation tests shall be conducted to prove the setup meets the free-free conditions. The reference free-free condition is a rotor hanging by a finger from the rotor hat, as depicted in SAE Technical Paper 2010-01-1688. The support setup used must not induce a frequency shift of more than 1% from the reference free-free condition. Ambient temperature should be 20 °C ± 4 °C. Placing the test object on foam is another acceptable alternative. The foam rubber used to simulate the free-free conditions is a polyurethane open cell foam based on polyether or polyester chemistry. The two critical properties of this foam are:

- Density (ISO 845): Between 24 and 57 kg/m^3.

- Compression force deflection at 25% (ISO 3386-1): Between 1.3 kPa and 3.4 kPa.

See Figure A1.

4.1.2 Excitation Method

A small impact hammer, as specified in Table 1, shall be used to impart a single pulse of a short duration. Impact the rotor in one or more directions depending on the targeted modes. At least one of these directions needs to be perpendicular to the brake plate. The use of a shaker is also valid.

4.1.3 Response Sensor

The response sensor shall sense rotor plate motion radiated from this motion. The response sensor shall either be a laser doppler vibrometer or accelerometers.

4.1.4 Setup Documentation

Document the used rotor setup with a picture and a value for variation from the reference free-free condition.

4.2 Instructions - Part A - Rotor Modal Analysis

4.2.1 Data acquisition parameters and equipment specifications:

Table 1 - Data acquisition and equipment specifications

DAQ Setting	Specifications
Frequency bandwidth	0 to 17 kHz
Minimum frequency sampling rate	Greater than 2x the sampling frequency
Minimum averages per measurement point	3
Frequency resolution	8 Hz
Analyzer FFT lines	Minimum of 1600
Windowing	Rectangular window for impact testing, exponential for response
Test piece isolation	See 4.1.1
Small impact hammer	Sensitivity: ≥20 to 25 mV/N Frequency range: 1 to 20000 Hz (-10 dB) Maximum range: ±220 N
Shaker(s)	100 to 200 N maximum (sine) rating Low armature mass and support stiffness
Uniaxial accelerometers	Mass: <2.0 gm Sensitivity: ≥1 mV/(m/s^2) Frequency range: 1 to 20000 Hz (±3 dB) Maximum range: 500 m/s^2 Resolution: >0.0005 m/s^2 Transverse sensitivity and non-linearity: ≤5% and ≤1%
Triaxial accelerometers	Mass: <5.0 gm Sensitivity: ≥1 mV/(m/s^2) Frequency range: 1 to 20000 Hz (±3 dB) Maximum range: 500 m/s^2 Resolution: >0.0005 m/s^2 Transverse sensitivity and non-linearity: ≤5% and ≤1%
Laser doppler vibrometer	Sensitivity: 1 to 1000 mm/s/V Frequency range: 1 to 20000 Hz (at >5 mm/s/V) Resolution: 0.3 to 10 µm Non-Linearity: ≤2.5%
Force transducer(s)	Sensitivity: >10 mV/N Maximum range: 450 N

4.2.2 Mount triaxial (or uniaxial in successive directions) accelerometers or specify laser doppler vibrometer measurement points as appropriate to identify brake rotor modes up to 17 kHz uniquely. See Figures B1 through B3 for a sample geometry of the brake disc, with component geometry and sample laser vibrometer measurement points.

4.2.3 Use a minimum of 40 points evenly distributed on the rotor's brake plate. See Figure B2.

4.2.4 The correlation to finite element models may require additional measurement points and need to be identified through a pretest measurement point analysis.

4.2.5 A method for discerning the in-plane modes, attach small blocks to the rotor cheeks. See Figure B4. The blocks should meet the following criteria:

- Made out of aluminum
- Dimensions: 10 x 10 x 10 mm to ensure sufficient surface area for the hammer impact and to attach the accelerometer.
- Block mass should be approximately 2 g.

4.2.6 Impact the block in the direction axial to the accelerometer. Look for the first two "in-phase" frequencies in imaginary or real versus Hz plot as an indication that both cheeks of the rotor are moving in the same direction. See Figure B5.

4.2.7 Document the measurement geometry, data acquisition, and test equipment.

4.2.8 Include a drawing or image showing the x, y, and z coordinates of each measurement point in the report.

4.2.9 Appendix C illustrates the recommended input points for the impact hammer force for the brake rotor in the free-free condition. Similar force input points may be used for rigid (mounted on rigid dyno fixture) or in-situ testing. The hammer impact direction can be at an oblique angle to excite all of the component modes. However, specific component geometry, in combination with certain acquisition equipment, may require the use of discrete orthogonal impact hammer directions and multiple input force locations to excite and identify all of the brake component modes. Mainly, if performing experimental modal analysis on rotors with a 3D laser vibrometer or triaxial accelerometers, if the modes of interest are nodal diametrical (ND) modes, the impact direction should be applied axially. However, if the modes of interest are in-plane compressional (IPC) modes, the impact direction should be applied tangentially or radially. See Figure C1 as an example of the impact location and direction.

4.3 Instructions - Part B - Production Verification of Rotor/Drum Mode(s)

4.4 Test Setup

4.4.1 Impact and Microphone

In this configuration, an impact device is used to excite rotor vibration. A microphone placed close to the brake plate is used to measure the sound radiated from rotor vibration. See Figure 1. The response captured by the microphone includes contributions from rotor in-plane and out-of-plane modes. To differentiate between modes, a separate finite element analysis or an experimental modal analysis is required to associate frequencies with specific mode shapes.

Figure 1 - Impact and microphone setup

4.4.2 Impact and Accelerometer

In this configuration, an impact device is used to excite rotor vibration, and one or more accelerometers are placed on the rotor brake plate to measure rotor vibration. Figure 2 illustrates the use of a triaxial accelerometer to identify out-of-plane versus in-plane vibration. This setup may be sufficient to classify rotor modes since motion in the perpendicular, radial, and tangential directions are observed. Impact position shall not coincide with a node of a mode that is under consideration. The mass of the attached accelerometer(s) shall be small enough so that they do not alter the frequency or modes of the rotor or drum. The attachment method used to secure the accelerometer to the surface should not interfere with the transmission of the compression or shear wave components into the accelerometer body.

Figure 2 - Impact and accelerometer configuration

4.4.3 Impact and Laser Vibrometer

In this configuration, an impact device is used to excite rotor vibration, and one or more laser beams are targeted onto the rotor brake plate to measure rotor vibration. Figure 3 illustrates the use of two laser beams to identify out of plane versus in-plane vibration. This setup can differentiate between in-plane and out-of-plane rotor modes. Impact position shall not coincide with a node of a mode that is under consideration.

Figure 3 - Impact and laser vibrometer configuration

4.4.4 Setup for Drums

This test procedure may be used for drum brakes using the setup illustrated in Figure 4 is a set up that may use microphone, accelerometer, or laser sensors.

Figure 4 - Set up for drums

4.6 Data Acquisition

4.6.1 Dynamic Analyzer

A dynamic analyzer is the preferred means of collecting transfer functions for rotor modal frequencies.

4.6.2 Equipment Input Amplifier

Dynamic range of the input channels is preferred to be with variable gain type.

4.6.3 Digitization

If enough bit resolution is available, a fixed range input channel may be used.

4.6.4 Equipment Signal-to-Noise Ratio

Signal-to-noise ratio of the vibration signal should be better than 72 dB.

4.6.5 Impact Triggering

An auto-trigger impact capability is preferred.

4.6.6 Windowing

A rectangular window for the impact input signal and exponential window for vibration signal is the preferred setting.

4.6.7 Differential Input

Use test equipment that has signal differential input when using voltage type sensors.

4.7 Signal Process

4.7.1 Averaging

An averaged transfer function is the preferred analysis process.

4.7.2 Frequency Resolution

Frequency resolution should be better than 3 Hz. (This may be obtained by sampling at 12.8 kHz, collecting 6400 points for 0.5 second frame, and carrying FFT analysis using the full 6400 points resulting in a resolution of 2 Hz over 6400 Hz.)

4.7.3 Transfer Function

The transfer function may be used in its accelerance (a/f), mobility (v/f), or compliance (x/f) forms. Sound pressure may also be used as output (Pa/N), but no differential is allowed in this case.

4.8 Mode Selection for Production Measurement

Use test equipment to trace product response and confirm modal profile to specified values. Identify frequency modes to be measured that assure consistency of mode identification—Figure 5 identifies acceptable modes, and Figure 6 identifies potential modes that could cause an error in production measurements. Choose only out-of-plane modes for production mode measurement/verification.

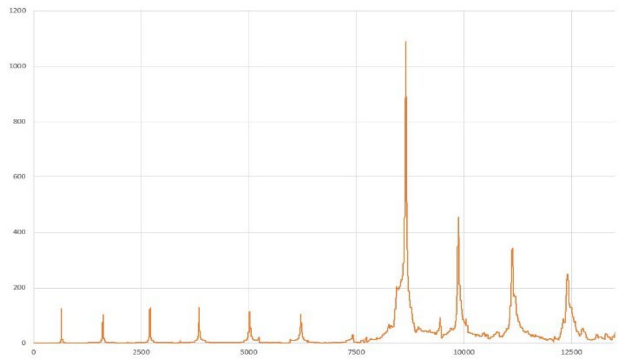

Figure 5 - Clearly defined response

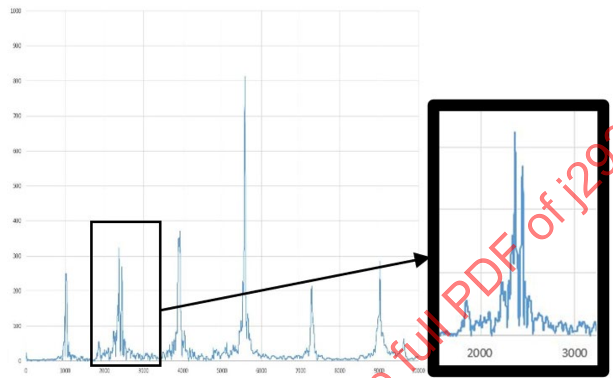

Figure 6 - Dual peak response

4.9 Mode Measurement

Typically, measurement of three modes is sufficient to verify frequency profile for production measurement.

Accurate measurement of rotor frequencies higher than 8 kHz may result in poor mode definition in the production environment. Select frequency modes below this value for consistent evaluation of rotor frequency profile and ongoing measurement

Document the measurement geometry. Document the data acquisition and test equipment.

5. DATA

5.1 Part A

5.1.1 Calculations

Determine the natural frequencies and mode shapes of each brake rotor or drum from 0.1 through 17 kHz. At a minimum, identify the frequencies of second through tenth ND modes; first, second, and third IPC modes. See Figures D1 and D2. IPR modes are not typically of significance for squeal and are usually not reported but the shapes are shown for reference. Use industry-standard software to identify the mode shapes. For the FE component model correlation, specify normal/real modes during modal parameter estimation

5.1.2 Interpretation of Results

Complete a mode summary table and produce summation FRF plots for the rotor. Also include any pictures or animations of mode shapes of interest (e.g., near brake squeal frequency). See Tables D1 and D2.

5.2 Part B

5.2.1 Calculations

Determine the natural frequencies of each brake rotor or drum from 0.1 through 8 kHz. At a minimum, identify the frequencies of second through fourth ND modes.

5.3 Test Documentation

Document all test information in 5.2. Document all available information on the measured component. See Table D3.

6. SAFETY

Contact the appropriate site Safety and Health personnel for further direction and guidance in these matters.

7. REPORTING

7.1 Modal Classification - Part A

It is recommended to classify that rotor modes before reporting. See Figures D1 and D2.

7.2 Results Tabulation - Part B

See Table 2. Use a unique number identifying the rotor and document the test date. Report mass with a 1 g of resolution. Frequencies are reported to 1 Hz, even though the resolution of measurement may be larger (<3 Hz). First three out-of-plane (ND) modes, second in-plane radial (two IPR) mode, and first in-plane compressional (1 IPC) modes are reported for tests with no prior knowledge on tested data, or if verification requires these modes. For quality control of larger batches, mass and first mode may be sufficient.

Table 2 - Sample tabulation of results

Rotor ID	**General Identification**	**Mass kg**	**2 ND Freq Hz**	**3 ND Freq Hz**	**4 ND Freq Hz**	**1 IPC Freq Hz**	**1 IPR Freq Hz**

8. NOTES

8.1 Revision Indicator

A change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

PREPARED BY SAE BRAKE NVH STANDARDS COMMITTEE

APPENDIX A

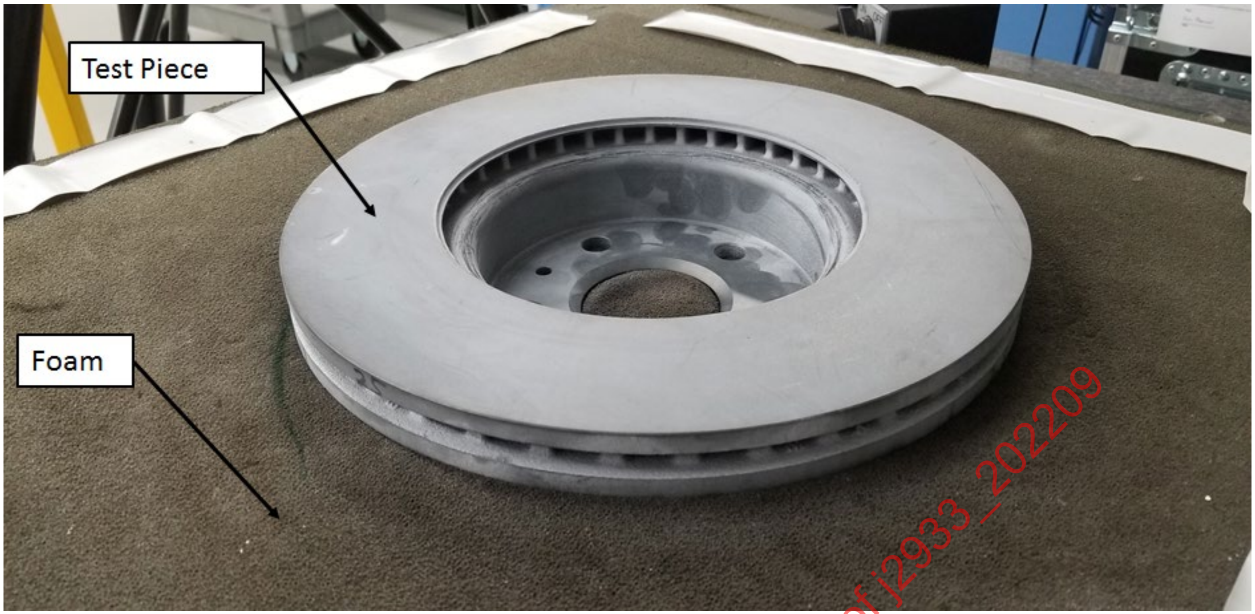

Figure A1 - Foam used to support brake components in free-free condition

APPENDIX B

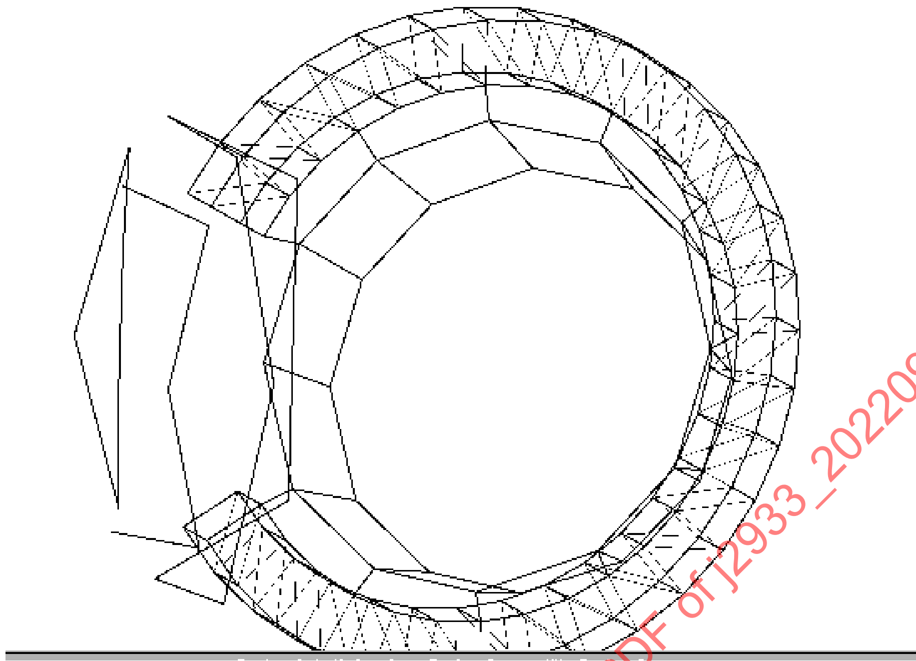

Figure B1 - Disc brake corner and component geometry example

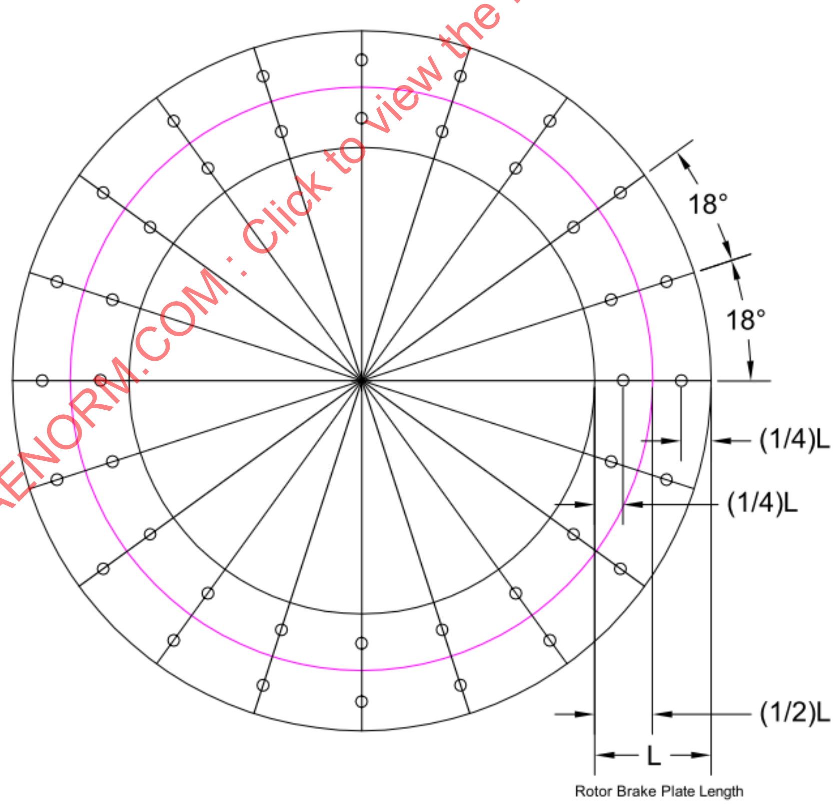

Figure B2 - Minimal point placement on rotor

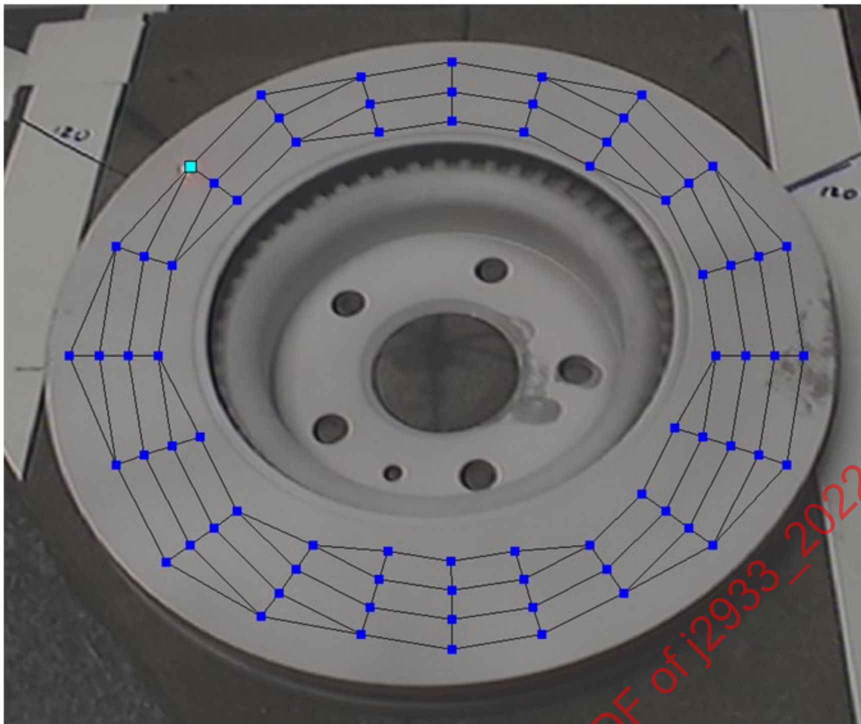

Figure B3 - Rotor example laser vibrometer measurement points

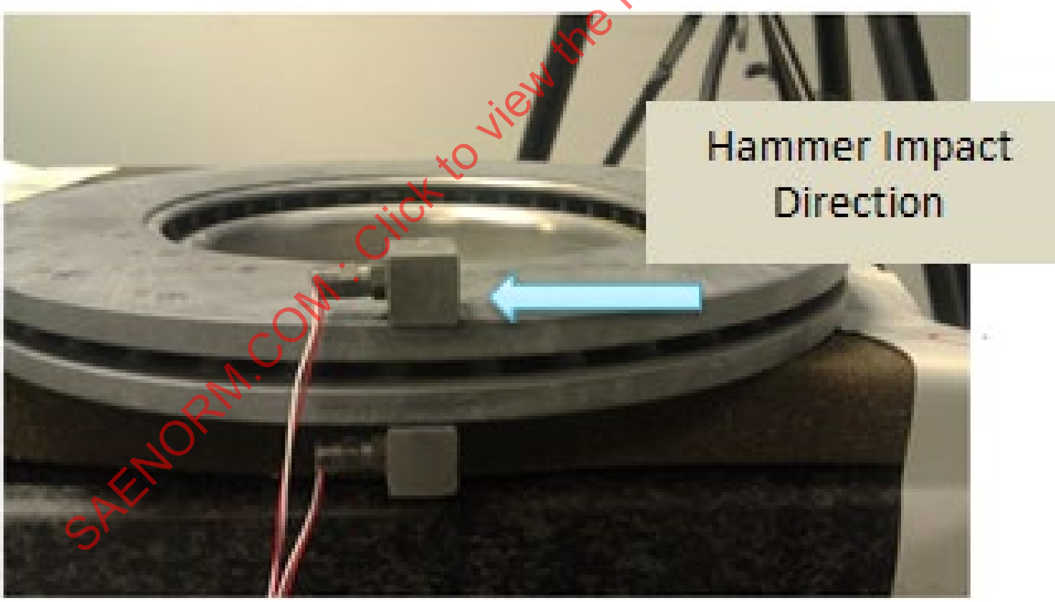

Figure B4 - Rotor in-plane mode alternative measurement method

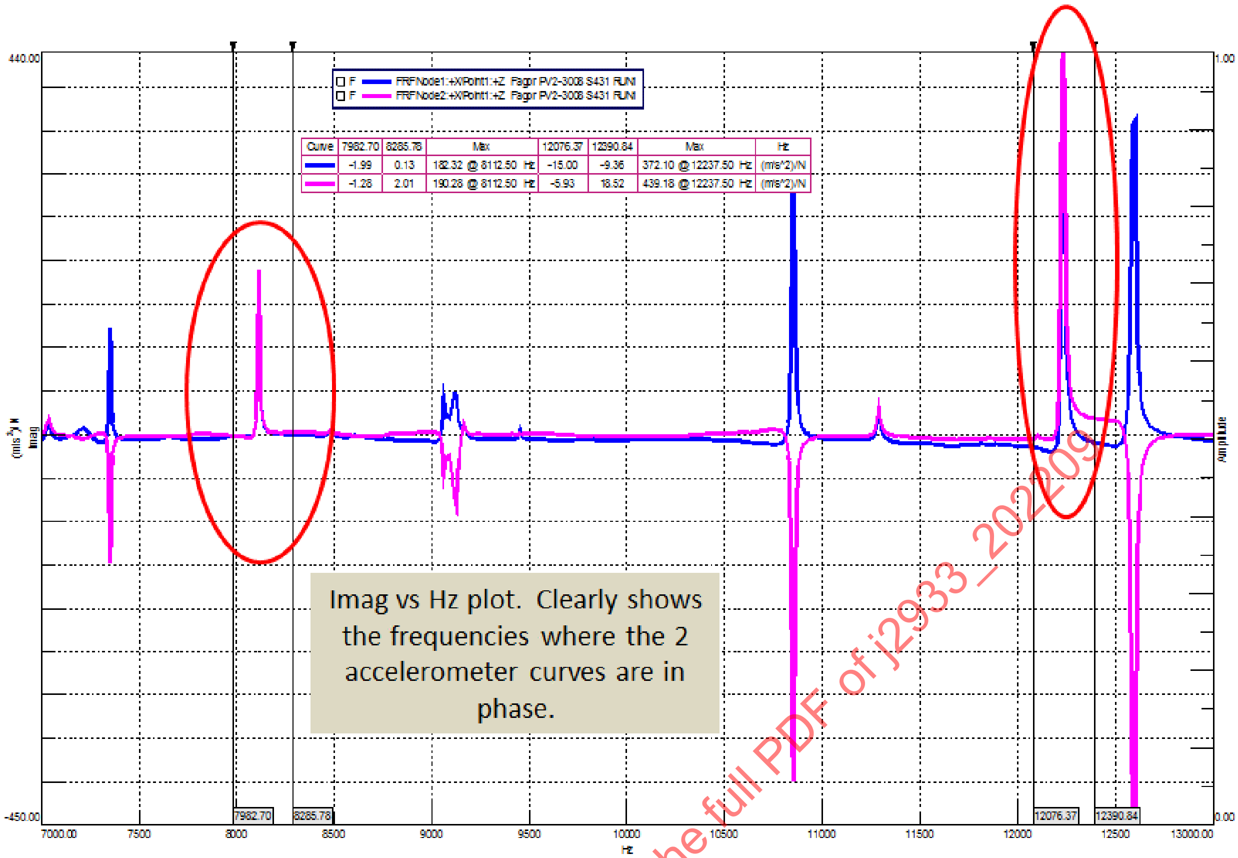

Figure B5 - Identifying rotor in-plane modes