CASE STUDY

Denmark

Automotive

PULSE, Software, Transducers

Meneta Advanced Shims Technology A/S
Brake Squeal Investigations using Acoustic Holography

Squeal can be a major problem in the development of new automotive disc brake systems. The squeal can be loud and persistent or transient, but it is always annoying. Brake squeal is one of the largest warranty issues for automotive manufacturers throughout the world. Therefore, increasing the knowledge of the parameters that generate squeal is one important contribution to the extensive research and development work currently being performed. The vibration motions of the brake components during squeal have been extensively studied using a variety of measurement techniques. These include acoustic holography, but until now, with limited success. This case study describes the use of cutting-edge acoustic holography technology to measure the disc motion.

A large PULSE™ system, Non-stationary STSF Type 7712 software and arrays of up to 100 microphones were used to make the study. Not only can the vibration pattern be identified, but also the existence and direction of travelling waves can be seen. Acoustic holography also reveals some interesting factors in the wave propagation of a squealing brake disc. This is due to the ability of acoustic holography to measure short transient events at high resolution.

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Brüel & Kjær thanks John Flint for his help with the writing of this case study.

The Company and its History

MENETA A/S is located at Odense, some 150 km (93 miles) west of Copenhagen, Denmark. Originally established in 1953, the company became part of the Danish ROULUNDS Group in 1988 and today employs about 100 people. The company manufactures pressed steel components and has its own tool design and manufacturing facilities.

A subsidiary company, Meneta Advanced Shims Technology A/S, specialises in the manufacture of anti-noise shims for use in the production of disc brake systems. The base material is steel or stainless steel, with a wear- and oil- resistant rubber coating vulcanized to one or both sides of the shim.

The manufacturing process ensures that the material has excellent noise insulation properties for disc brake pads. Meneta's stringent quality control procedures ensure that its high quality products are in accordance with ISO 9001:2000 before shipment to all major European disc brake manufacturers. Some 15 million shims are produced annually.

Engineering Expertise

John Flint has worked at Meneta Advanced Shims Technology A/S for three years and is its R&D Manager. John has worked in the brake industry since 1986. He recently gained a Ph.D from the University of Southern Denmark. The subject of his thesis was a detailed investigation into the parameters that cause squeal in disc brakes. The measurements were made at Meneta's premises with the assistance of Jørgen Hald, Ph.D, of Brüel & Kjær's Innovation Group.

Disc Brake Squeal

John says, "Disc brake squeal is a major problem in many new designs of brakes as well as when implementing proven designs of brake systems in new applications. Extensive test and analysis have been conducted with the aim of solving this problem. Knowing the vibration patterns of the brake components is a major step in understanding the problem and its nature".

He continues, "The brake disc is a major source of emitting squeal noise. It is one of the components in the friction pair, disc and pad, that together act as the noise generator. For this reason the mode shape of a squealing disc brake is of special interest. Initially the measurements were performed on a simple disc brake specially designed for the study of mathematical modelling of disc brake squeal".

Acoustic Holography

Fig. 1
Three PULSE Type 3560 E frames were stacked together to provide up to 132 channels. This array uses 120 microphones

Time Domain Near-field Acoustic Holography techniques were used to capture the transient response during a squeal. Measurements and analyses were performed using a Brüel & Kjær PULSE system. This comprised three Type 3560 E frames stacked together to provide a total of 132 channels. In addition to the standard Noise and Vibration Analysis Type 7700 software, Acoustic Test Consultant Type 7761 and a Non-stationary STSF Type 7712 system were used. Here, sound pressure is measured by microphones in a grid of points in a plane close to the sound source. The grid covers the area of the source.

The sound pressure p is a function of space and time, and it fulfills the homogeneous wave equation:

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = 0$$

where t is time and c is the propagation speed of sound. A set of combined spatial and temporal Fourier transforms can describe the solution to the equation in any plane parallel with the measurement plane. For each calculation point, the pressure and particle velocity time signals are obtained. The air particle displacement and the sound intensity can be calculated based on this. In particular, the air particle displacement in a plane coinciding with the plane of the structure can be calculated. An air particle at the surface has the same displacement in the direction perpendicular to the structure as the displacement of the surface, and in this indirect way the vibration of the structure is estimated from the measurements.

Non-stationary STSF Type 7712

Non-stationary STSF Type 7712 enables the results to be displayed as animated maps overlaid on a photograph of the test object, showing the displacement of the structure as a function of time. These displacement maps have a certain resolution limitation. This is because of the limited possibility of reconstructing fading sound wave components. Such wave components decay exponentially in their propagation away from the source. The resolution will be approximately equal to the array grid spacing.

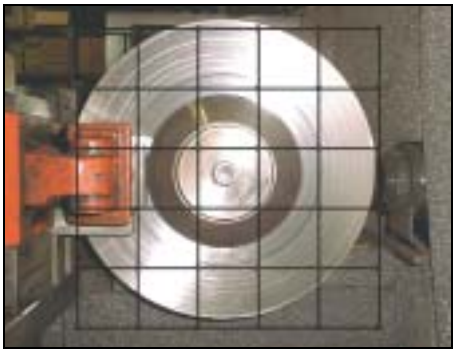

Fig. 2
6 × 6 grid of 36 microphones was used to measure noise from the simple test brake

Non-Stationary STSF Type 7712 is designed so that it can be set up and calibrated quickly. Several sound events from different brake systems were measured in a short time. An array of 36 microphones was used for this simple test brake. During the test several squeal events occurred, but the 5 cm spacing of the microphones did not allow analysis at frequencies above 3.2 kHz. This restriction was set in order to prevent spatial aliasing effects from showing up in the results

Mode Shape at 1800 Hz

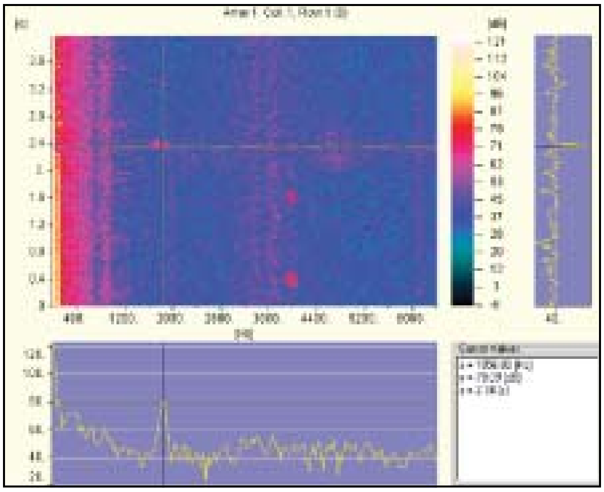

Fig. 3
A time-frequency graph of a noise measurement on the simple test brake. 1856 Hz and a 1738 Hz squeal events follow soon after each other and are seen 2.34 s into the measurement. The data is sampled with 16 K samples per second

One of the favourable properties of the non-stationary STSF method is its ability to process events of very short duration. Fig. 3 shows an example of a measurement, where two squeal events are visible at 4 kHz. For the microphone spacing used in this measurement, this frequency is above the limit where analysis is possible with STSF. At approximately 1800 Hz, two other events occur within a very short time interval. The first event is at 1856 Hz and the second at 1728 Hz. In total they last less than 0.1 second.

One period of oscillation from the squeal event at 1856 Hz can be seen in Fig. 4. It is processed to show displacement at the plane of the disc. This period is chosen at the time where squeal just starts and the amplitude builds up. Two nodal diameters are visible on most of the pictures. The nodal positions are rotated 180° in the clockwise direction during this one period of oscillation. This means that there is a travelling wave in the opposite direction to the rotation of the disc. The rotational speed of the disk during this measurement is 50 rpm. This means that the physical rotation of the disc during one period of oscillation is very small.

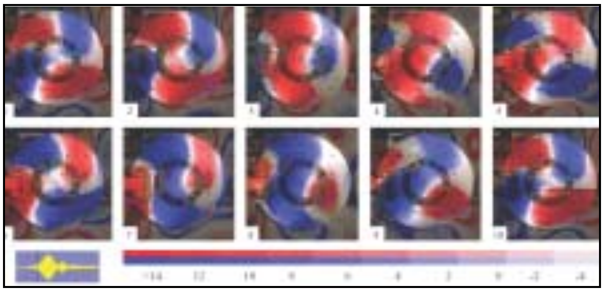

Fig. 4
The squeal event at 1856 Hz is shown for one period of oscillation. The period is selected at the time of rising amplitude

During an animation of the displacement, it can be seen that the clockwise rotation of the nodal positions stops, when the amplitude is no longer increasing. When the amplitude is declining, the nodal positions are stationary, as seen in Fig. 5.

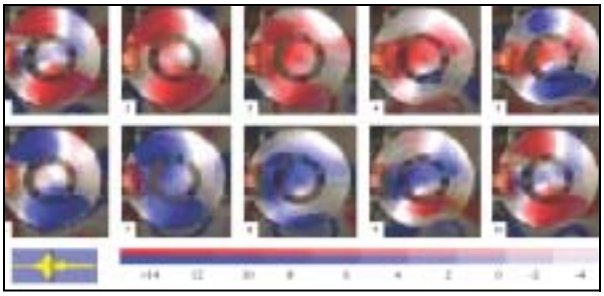

Fig. 5
Displacement oscillation of the squeal event at 1856 Hz when the amplitude is declining. The sequence shows a standing wave

In the next squeal event at 1728 Hz, a clockwise travelling wave can be identified while the displacement increases. The wave becomes stationary as the amplitude decreases and the waves start to travel in the opposite direction. The rotation of nodal lines in counter clockwise direction can be seen on the sequence of pictures in Fig.6.

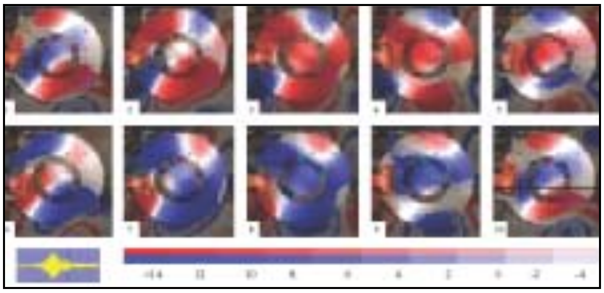

Fig. 6
The displacement calculated from the measured sound pressure for the squeal event at 1728 Hz

Additional analysis of some measurements on this brake can be found in the SAE paper 2003-01-3319 entitled “Travelling Waves in Squealing Disc Brakes Measured with Acoustic Holography”, by John Flint and Jørgen Hald.

This paper also presents results of measurements on an automotive disc brake and it includes accelerometer measurements of the in- and out-of-plane motion of the disc.

Summary

John says, “The measurements were initially made on a simple disc brake and, using acoustic holography techniques, the vibration of a disc during squeal was measured”.

Acoustic holography measures the radiated sound pressure, and then solves an inverse radiation problem to estimate the air particle displacement at the surface of the structure. This displacement coincides with the vibration of the structure itself.

In the process of physical sound radiation and subsequent computational reconstruction of the source vibration through an inverse calculation, some information will inevitably be lost. Acoustic holography, in its present form, does not take into account that the surfaces emitting sound may be located at different distances from the array of microphones. The technique is also sensitive to reflections of sound from nearby structures, and in this analysis, the measurement object was not very well positioned.

Nevertheless, where a priori knowledge of the structure and of its modal properties can be used in interpreting the results, valuable information can be extracted from the measurements.

The acoustic holography measurements show some deviation from regular nodal diameter modes.

Fig. 7
John Flint uses a Brüel & Kjær sound level meter during the setup phase of the study

Fig. 4 and Fig. 5 do not show a classic two nodal diameter mode. Especially on the right-hand side and on the lower half of the disc, some deviations occur. This may be due to reflection of sound from the wall and floor. The wall can be seen at the right hand side of Fig. 2. Despite the reflections, a systematic deviation from a classic 2 nodal diameter mode can be seen in Fig. 4. The nodal lines are not straight, but are curved backwards (counterclockwise) as the nodal lines extend from the inner radius to the outer periphery.

John says, “The measurements with acoustic holography do not provide the same spatial resolution as conventional holography”.

He concludes, “However, it can provide a wealth of information on the behaviour of a system. No other available measurement method can deliver results with a comparable resolution both in space and time. The ability to study the vibration pattern of the complete disc with 16 000 frames per second at a reasonably high spatial resolution is difficult to match by other techniques. A scanning laser vibrometer may deliver results with fine spatial resolution, but at the expense of a long averaging period. A short transient event cannot be studied with this method. Conventional optical holography delivers high-resolution images, but the time resolution cannot be high for prolonged periods of time”.

Measurement methods based on averaging, like a scanning laser vibrometer, will not be able to catch short transient events or the initial build-up of oscillations leading to sustained squeal. In addition, the time averaging may give misleading results when it averages over a long period, where the squeal amplitude rises and falls. This will be the case if a rise and fall in amplitude are associated with a change of direction of a travelling wave component, as was the case in the present measurement.

Key Facts

- Measurements and analyses were performed using a Brüel & Kjær 132-channel PULSE system with Noise and Vibration Analysis Type 7700 software, Acoustic Test Consultant Type 7761 and Non-stationary STSF Type 7712 system
- Measurements were made with arrays of up to 100 microphones
- Travelling waves could be measured during brake squeal
- The waves could be travelling in different directions at different points in time in the same squeal event
- Acoustic holography has demonstrated its ability to measure short, transient events with a moderate resolution in space and a high resolution in time, and has been particular helpful in the analysis of travelling waves in disc brakes
- The study provides a fundamental understanding of the parameters that cause squeal in disc brakes
- “No other available measurement method can deliver results with a comparable resolution both in space and time”
- “The ability to study the vibration pattern of the complete disc with 16 000 frames per second at a reasonably high spatial resolution is difficult to match by other techniques”

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