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Traveling waves in squealing disc brakes measured with acoustic holography

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ABSTRACT

Disc brake squeal can be a major problem during development of new brake systems. Squeal can be loud and persistent or fugitive but nevertheless annoying. Increasing the knowledge of the mechanisms generating squeal is one important contribution to the extensive research and development work being performed in order to solve the problems. The vibration motions of the brake components during squeal, especially the disc, have been studied intensively, and the existence of standing or traveling waves and the direction of such waves have been debated. Several measurement techniques have been employed in order to reveal the nature of the disc motion, including holography, scanning laser vibrometry and rowing accelerometers in the disc. Also acoustic holography has been employed previously - see for example [2] - but this paper documents the ability of acoustic holography to create new knowledge about disc brake squeal through measurement of the disc motion. Not only the vibration pattern can be measured, but also the existence and direction of traveling waves in squealing disc brakes can be recognized. At the same time acoustic holography reveals some interesting characteristics in the wave propagation of the squealing brake disc not previously reported. This discovery was made possible by the ability of acoustic holography to measure short transient events with a high resolution both in time and space.

INTRODUCTION

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 purpose of solving these problems. Increasing the understanding of the mechanism generating squeal is one of the important tasks to pursue. Knowing the vibration patterns of the brake components is one step in understanding the problem and its nature. The brake disc is a major source of emitting squeal noise, and at the same time it is one of the two parts in the friction pair – disc and pad – that acts as the generator of the noise. For this reason the mode shape of a squealing disc brake is of special interest.

The measurements reported in the first part of this paper were performed on a simple disc brake specially designed for the study of mathematical modeling of disc brake squeal [1]. The last part of the paper reports measurements performed on a standard disc brake for passenger cars.

ACOUSTIC HOLOGRAPHY

The method of Time Domain Near-field Acoustic Holography [2] has been employed in order to capture the transient response during squeal. Measurements and analyses were performed using the Brüel & Kjær Type 7712 Non-Stationary STSF measurement system. Here, sound pressure is measured by microphones in a grid of points in a plane close to the sound source. It is assumed that 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

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

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 (1) in any plane parallel with the measurement plane, [2]. For each calculation point, the pressure and particle velocity time signals are obtained. Based on that information the air particle displacement and the sound intensity can be calculated. 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 in that direction, and in this indirect way the vibration of the structure can be estimated from the measurements. Results can be displayed as animated maps overlaid on a photo of the structure. In this way the displacement of the structure as a function of time can be shown. It should be noted that these displacement maps would

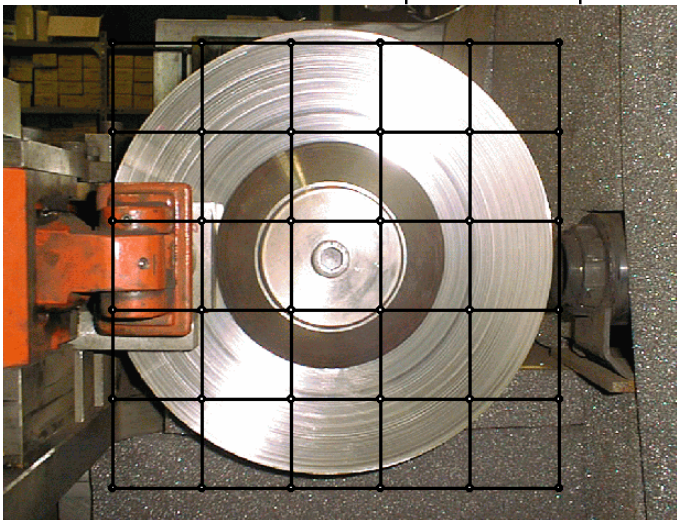

Figure 2. Locations of microphones in the 6×6 array used for measurements on the simple test brake.

have a certain resolution limitation. This is because of the limited possibility of reconstructing evanescent sound wave components. Such wave components decay exponentially in their propagation away from the source. The smallest possible resolution will be approximately equal to the array grid spacing.

The Non-Stationary STSF system is designed so that it is quick to set up and calibrate. Several sound events from different brake systems were measured in a short time. An array of 6×6 microphones as shown in Figure 2 was used for this particular simple test brake.

During the measurements on the simple test brake several squeal events occurred, but the spacing of the microphones did not allow analysis of any frequency above 3.2 kHz. This restriction is imposed in order to prevent spatial aliasing effects to show up in the results.

MODE SHAPE AT 1800 HZ

One of the favorable properties of the non-stationary STSF method is its ability to process events of very short duration. Figure 1 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 are occurring within a very short interval in time: the first event at 1856 Hz and the second at 1728 Hz. In total they last less than 0.1 second.

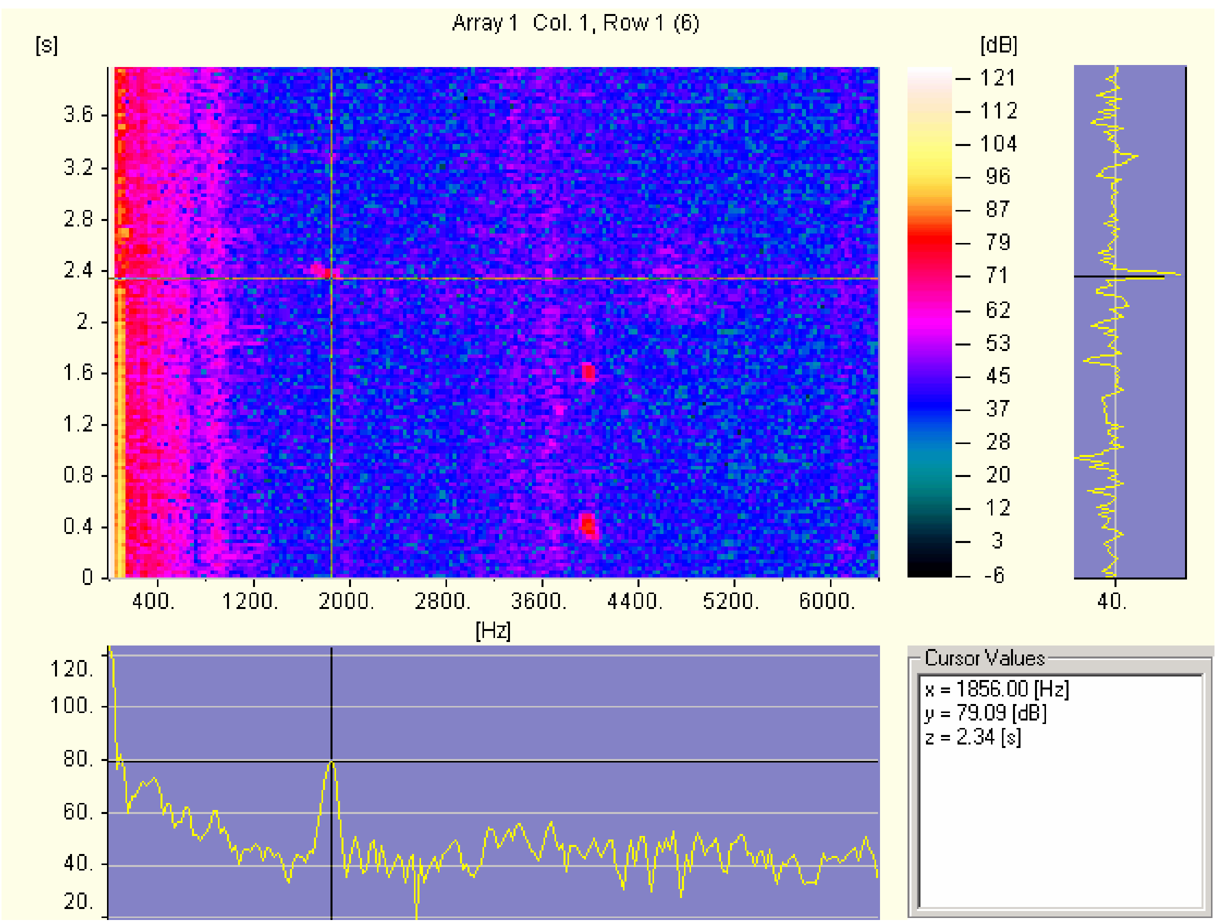

Figure 1. Time-frequency graph of a noise measurement on the simple test brake. An 1856 and a 1728 Hz squeal event following close after each other are visible 2.34 seconds into the measurement. The data is sampled with 16 K samples per second.

One period of oscillation from the squeal event at 1856 Hz can be seen in Figure 3. 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 traveling wave in the opposite direction of rotation of the disc. The rotational speed is 50 RPM, which means that the physical rotation of the disc during this one period of oscillation is less than 0.15°.

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 Figure 4.

Also in the next squeal event at 1728 Hz, a clockwise traveling wave can be identified while the displacement increases. The wave becomes stationary when the amplitude levels of, and as the amplitude decrease, the waves start to travel in the opposite direction. The rotation of nodal lines in counterclockwise direction can be seen on the sequence of pictures in Figure 5.

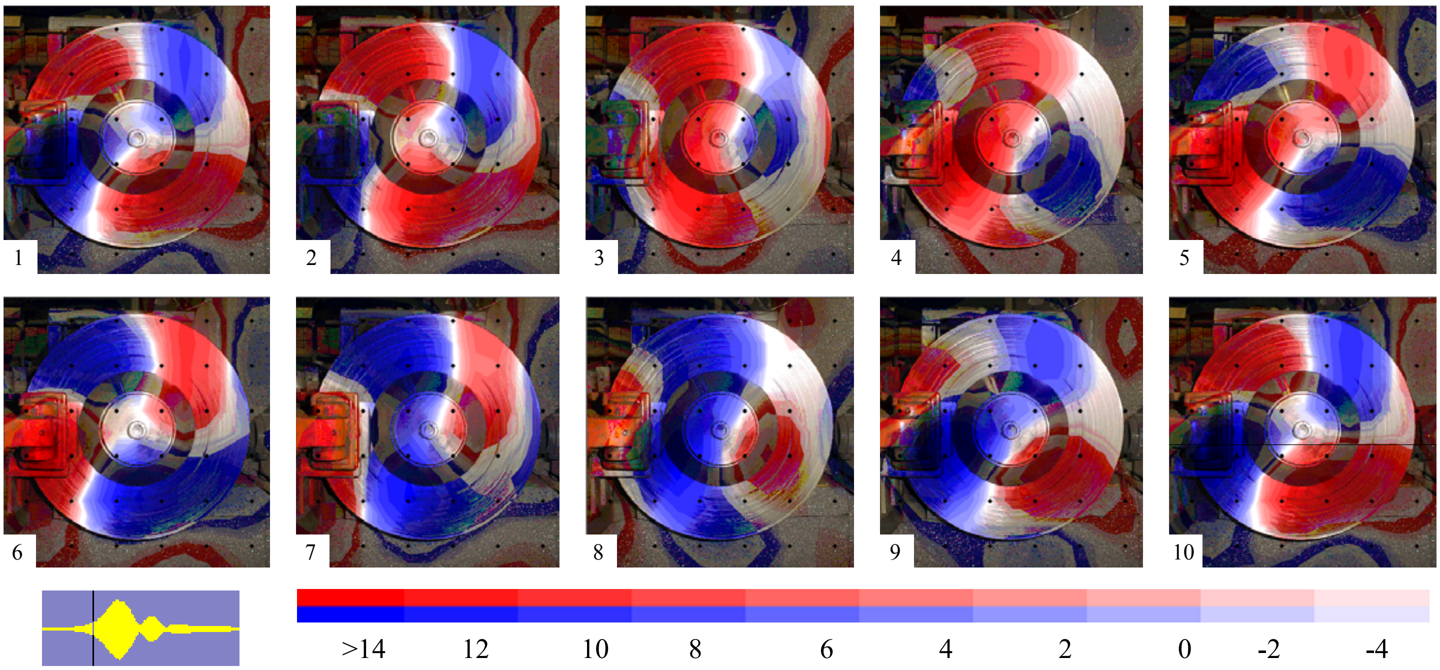

Figure 3. One period of oscillation in the squeal event at 1856 Hz. The period is selected at the time of rising amplitude as indicated on the lower left graph. The pictures show a wave traveling in the clockwise direction.

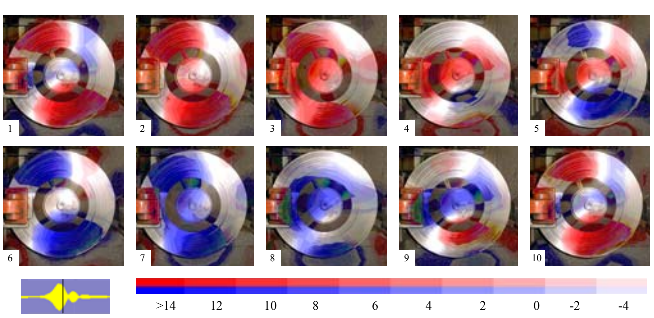

Figure 4. Displacement of the disc in the squeal event at 1856 Hz, when the displacement amplitude is falling. The series of pictures shows a standing wave.

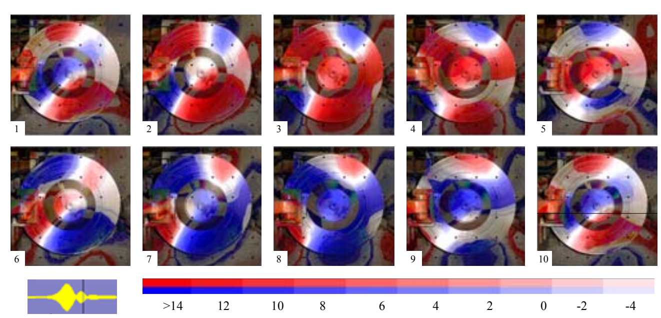

Figure 5. Calculated displacement from the measured sound pressure for the squeal event at 1728 Hz. This period of oscillation is from the time of declining amplitude of vibration, as indicated in the lower left graph. A counterclockwise traveling wave is seen.

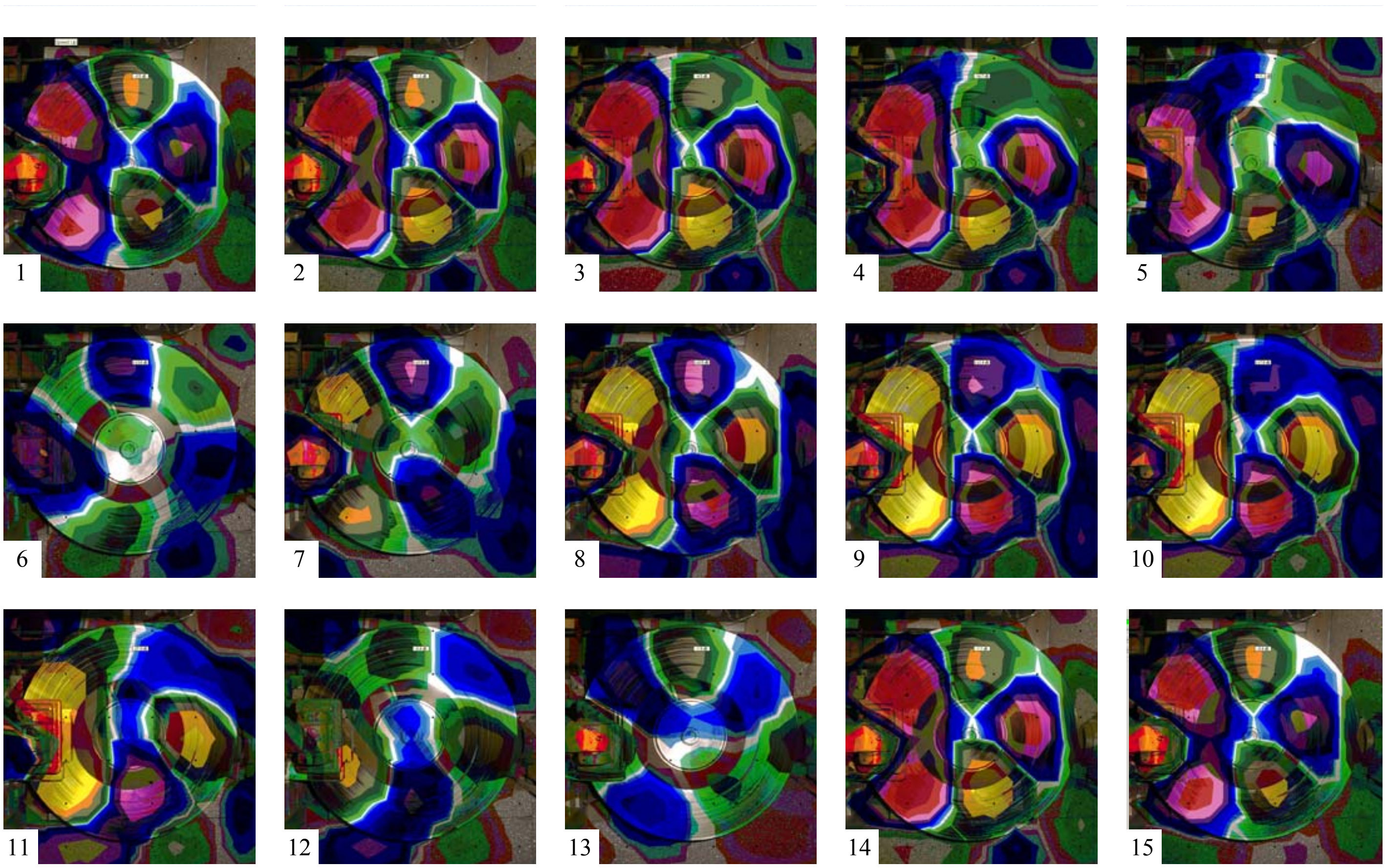

Figure 6. Air particle displacements at the surface of the disc. A three nodal diameter standing wave with a small clockwise traveling component is seen.

MODE SHAPE OF DISC AT 2500 HZ

Figure 6 shows 12 pictures of the air particle displacement calculated at the surface of the disc from a measurement with squeal at 2496 Hz. Maximum displacement is located in the region close to the pads. The pattern shows a three nodal diameter mode mostly exhibiting a normal mode stationary vibration, but with a small component of a wave traveling clockwise, i.e. against the direction of rotation of the disc. This squeal is longer than the previous squeal and varies in amplitude. Figure 6 is taken near a peak in the amplitude. Studies of the motion at different locations during the squeal show that the traveling wave components change in amplitude and direction in a way similar to the event at 1800 Hz reported in the previous section.

MEASUREMENT OF ACOUSTIC RADIATION FROM AN AUTOMOTIVE DISC BRAKE DURING SQUEAL

This section describes measurements with acoustic holography on a passenger car front disc brake. An array of 100 microphones was located as shown in Figure 7. The microphones were located a distance of 6 cm from the disc friction surface.

A 2800 Hz squeal was measured on this brake system. Figure 8 shows results from the measurement. The 15 images are taken from slightly more than one period of oscillation. In the third picture, three areas can be identified as having a large outwards deflection and

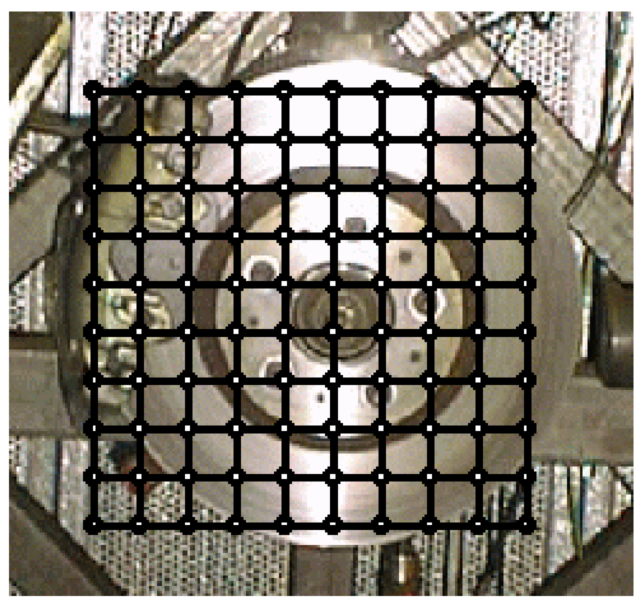

Figure 7. Location of microphones in a 10×10 array for measurements on automotive brake.

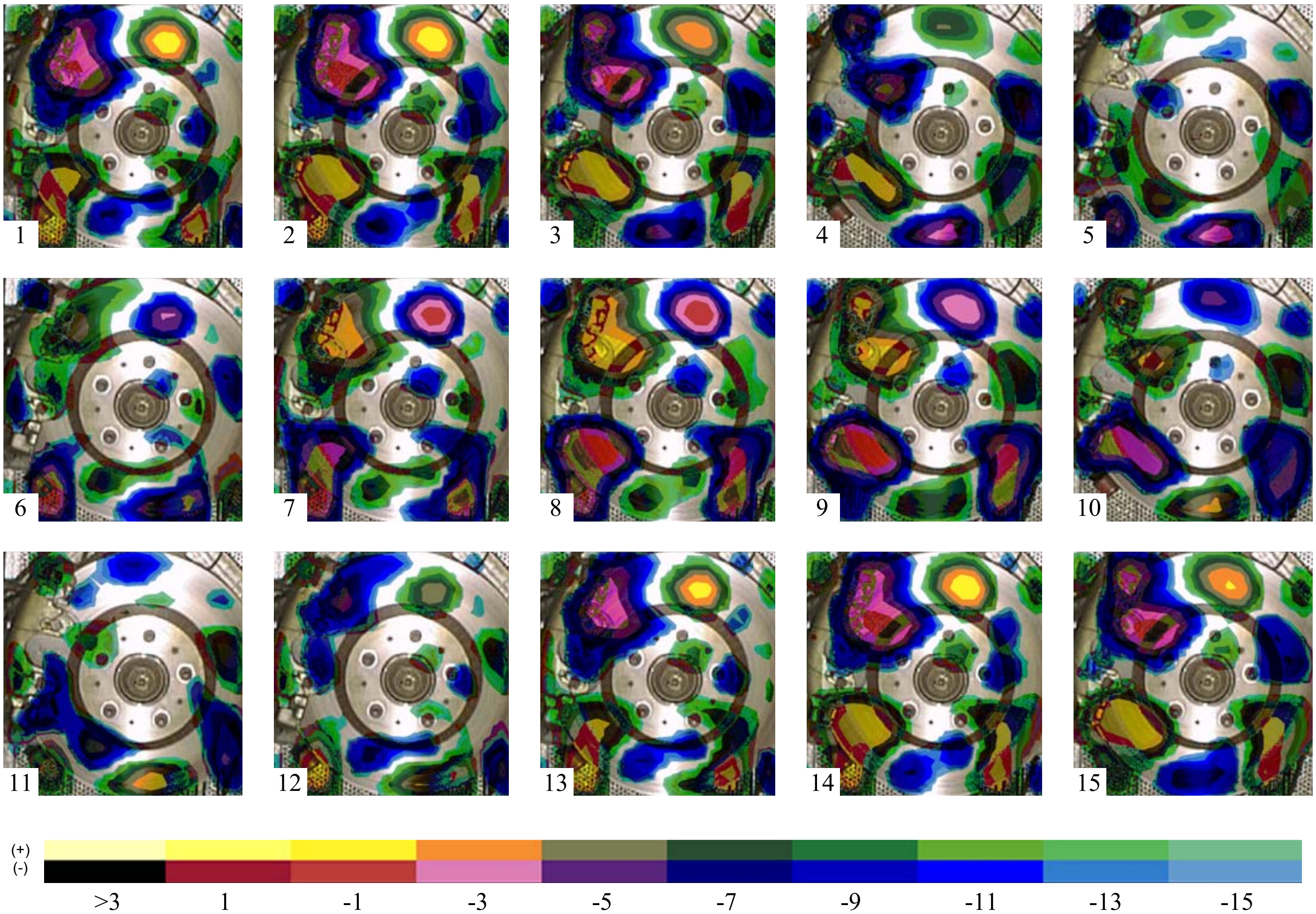

Figure 8. Acoustic holography of 2800 Hz squeal on an automotive disc brake system. The time step between two images is 0.0305 ms and the series corresponds to 1.28 period of an oscillation.

three as having large inwards deflection. This corresponds to a three nodal diameter mode on the disc. In the pictures with highest displacement (2, 8 and 14) the largest deflections are located at the same positions. In the pictures in-between the amplitudes are smaller, but the points of largest deflections are not stationary, i.e. they rotates. None of the pictures show zero vibration, so this indicates the existence of a complex mode of vibration. Hence the pictures illustrate a standing wave combined with a traveling wave. The direction of the wave may be identified from pictures 3 to 6, where the orange/green area on the upper half of the disc moves in a counterclockwise direction. This is the direction of rotation of the disc. The disc has rotated only very little during this one cycle of vibration, so the motion of the mode is not due to the rotation of the disc.

The one dimensional mathematical model of the brake system presented in [1] is capable of simulating instability at a frequency of 2700 Hz, which is close to the noise measured on the brake during car test and noise dynamometer test. Comparison of this result with the measurements of the mode shape on the brake during squeal (Figure 8) shows a good correlation both in number of nodal diameters and in the direction of the traveling wave.

Measurements with accelerometers in the disc have been made in order to verify that the out of plane displacement indeed was the dominating mode of vibration by this noise problem. Figure 9 shows the position of two accelerometers located in the disc: One was measuring in the out of plane direction and the other was measuring in the in-plane tangential direction. The measuring signals were transmitted from the rotating disc via a slip ring. Figure 10 shows the measured displacement, and it is clear from the graph that the motion is almost exclusively in the out of plane direction, i.e. in the direction that is measured by acoustic holography.

SUMMARY AND DISCUSSION

The first part of this paper has reported acoustic holography measurements of the vibration of a disc during squeal. Acoustic holography measures the

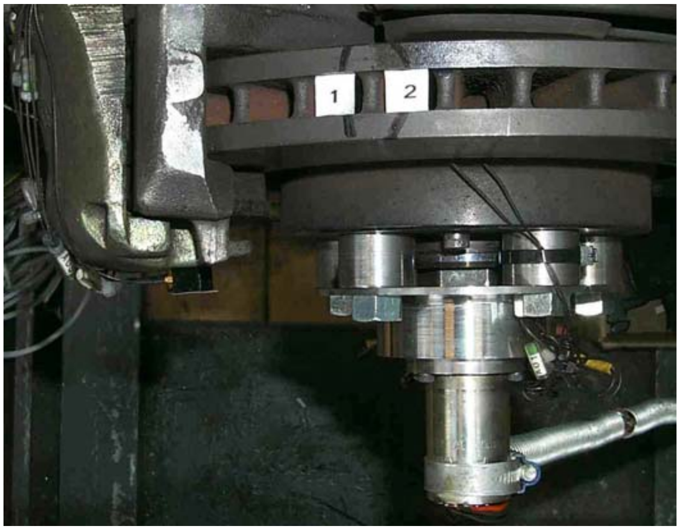

Figure 9. Location of accelerometers in the disc: 1 - Out-of-plane direction, 2 - In-plane direction. Note the slipring connecter for transfer of the signals in the lower part of the picture.

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 analyses, the measurement object was particularly ill positioned in that respect. Nevertheless, in a situation like this, 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. Figure 3 and Figure 4 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 Figure 1. Despite the reflections, a systematic deviation from a classic 2 nodal diameter mode can be observed in Figure 3: The nodal lines are not straight, but curved backwards (counterclockwise) as the nodal lines extend from the inner radius to the outer periphery.[1]

[1] This fact was first noted by Morten Hartvig Hansen, and it can be modeled mathematically by using complex coefficients on the functions giving the deflection along the radial lines [5].

The measurements with acoustic holography do not provide the same spatial resolution as conventional holography, cf. [3]. But it can still provide a wealth of information on the behavior 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 16000 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 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 buildup 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 rise and fall. This will be the case if rise and fall in amplitude are associated with a change of direction of a traveling wave component, as was the case in the present measurement.

The existence of traveling waves in squealing disc brakes has been documented by Talbot, Banawi and Fieldhouse [4]. The existence of a wave traveling in one direction at the onset of squeal, loosing phase speed to become a standing wave for stationary amplitude, and eventually change direction to become a wave traveling in the opposite direction, when the amplitude declines, is documented here for the first time. The direct link between traveling of the wave and the increase of vibration amplitude agrees well with instability predicted by eigenvalue analysis, see for example Flint and

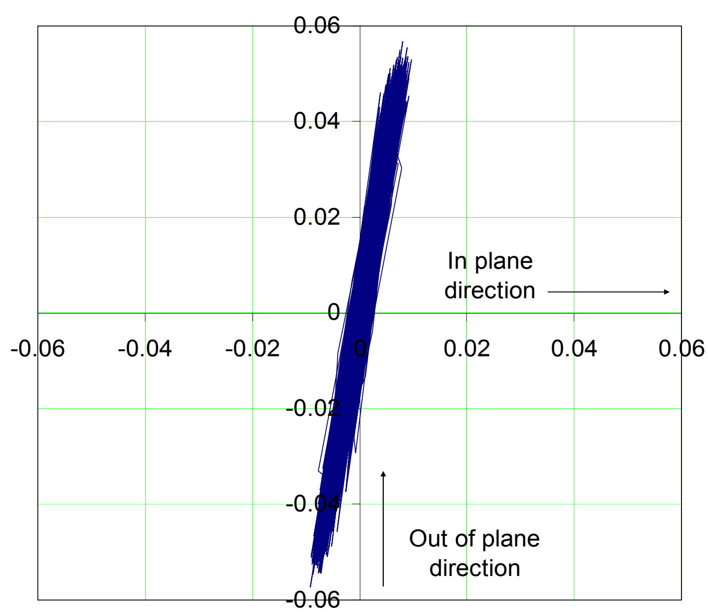

Figure 10. Displacement measured in out of plane and in-plane directions.

Hultén [6]. A complex eigenvalue with positive real part is associated with a complex eigenvector, and a traveling wave, as it can be a representation of such a complex eigenvector. A shift to a standing wave corresponds to the real part of the eigenvalue becoming zero, and this means that the amplitude no longer grows. This course of events is seen in these measurements with acoustic holography.

CONCLUSION

A number of important observations can be made from this investigation:

- Traveling waves were measured during squeal.
- For this type of squeal at 2800 Hz the oscillations of the disc were almost exclusively in the out of plane direction.
- The waves were traveling in different directions at different points in time in the same squeal event.
- The forward and backward directions of rotation of the waves were associated with the increase or decrease of the amplitude of the squeal.

These observations agree well with the general results from complex eigenvalue analysis, where the solutions are associated with traveling waves, and where stable and unstable solutions corresponds to waves in opposite directions.

As a conclusion it can be noted that the method of acoustic holography has shown its strength in relation to measuring short, transient events with a moderate to high resolution in space and a high resolution in time. This ability is particular helpful in the analysis of traveling waves in disc brakes.

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