APPLICATION NOTE

Using Non-stationary Spatial Transformation of Sound Fields to Investigate Transient Phenomena in Automotive Applications

Non-stationary Spatial Transformation of Sound Fields (NS-STSF) is a revolutionary technique for mapping noise in 3D-space and time. NS-STSF in effect allows you to film the noise emanating from a test object as a sequence of snapshots of instantaneous sound pressure using a microphone array. You can then map the noise distribution in time and space by transforming the measured sound-field to other planes, parallel to the measurement plane. All common sound-field descriptors such as SPL, intensity and spectral content are available from a single measurement. This system is the only truly transient implementation of the Acoustic Holography technique. The NS-STSF technique has many different applications including:

- unrepeatable noise events, such as brake squeal
- micro-phenomena, e.g., small impulses in otherwise stationary noise
- run-up measurements

Application Note

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Measurements

The following two examples cover two NS-STSF applications, which clearly distinguish the technique from scan-based acoustical holography implementations, such as STSF (Spatial Transformation of Sound Fields).

Capturing and Mapping a Transient Acoustical Event

The first example to consider is the measurement of disc-brake squeal. Since squeal noise is transient by nature and very difficult to reproduce in a controlled way, a scanning holography method is not a suitable solution. With NS-STSF, a single recording is sufficient to get detailed temporal and spatial information about the squeal-noise radiation.

Fig. 1 shows a picture of the part of the brake disc over which the measurement was taken with microphone positions indicated by dots. Because of the supporting structure, it was not possible to measure the entire area of the disc. As seen in the picture, an array with 6 rows and 12 columns was used to measure the upper half of the inside of the disc. The array element spacing was 5 cm, covering a frequency range up to approximately 3 kHz, and the distance from the disc to the array was approximately 10 cm. A 4-second recording with 3.2 kHz bandwidth was made.

Clearly, the array area did not cover the entire source, as normally required. In order to approximately meet this requirement, that part of the source outside the array area was shielded by absorbing material. Furthermore, by use of the *Velocity Windowing* technique and the use of a smaller dynamic range than normally applied in the reconstruction of evanescent waves, quite good results were obtained.

Fig. 1
Measurement area with dots indicating array microphone positions

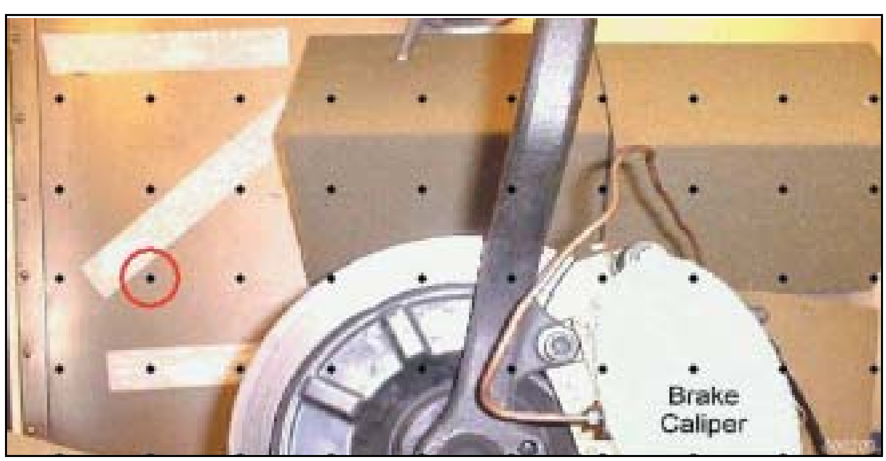
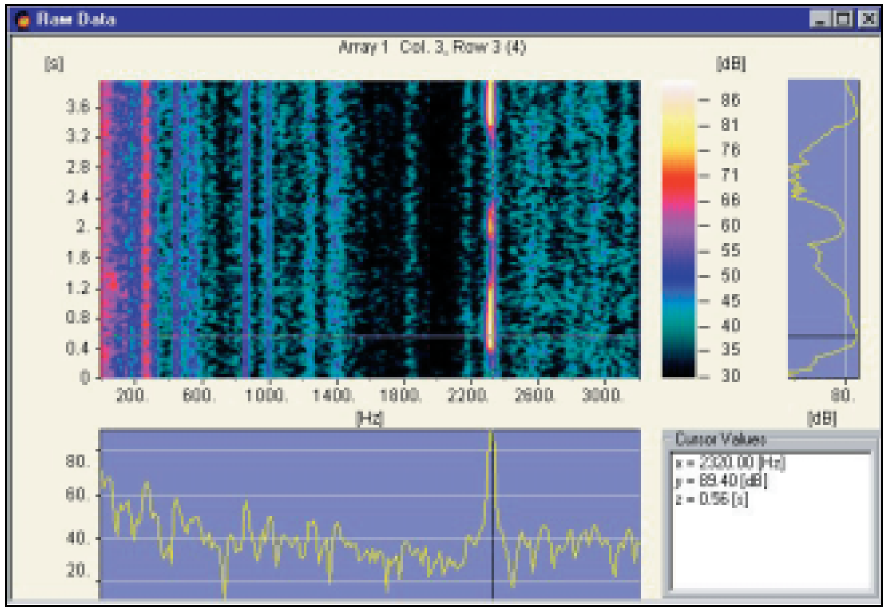
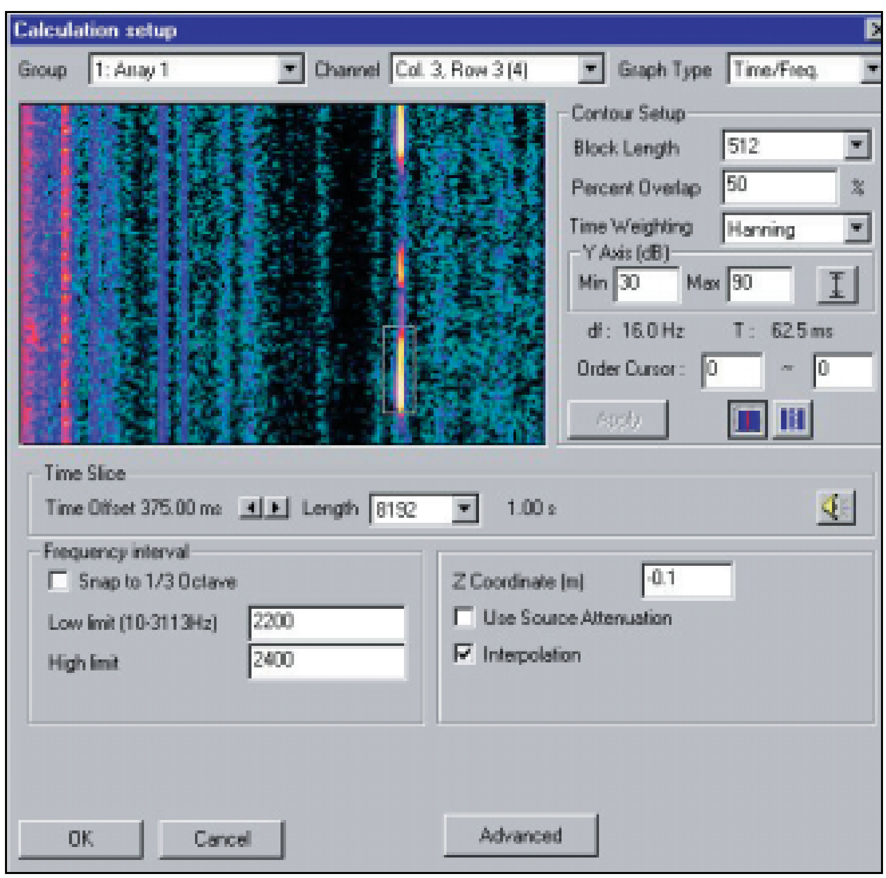


Fig. 2
Time/Frequency analysis in Raw Data view, i.e., only looking at measured signals – not calculated data



In order to inspect the temporal characteristics of the recorded squeal(s), a time/frequency analysis can be performed on selected microphone signals. In Fig. 2 the signal has been chosen from the array microphone in column 3, row 3, which is circled in Fig. 1. It can be seen that the signal is dominated by a narrow-band squeal component around 2320 Hz, and the 4-second recording period is seen to actually contain three separate, short squeals.

Fig. 3
Calculation Setup window



In order to calculate the sound field in some plane parallel to the array plane, a calculation setup must be defined (see Fig. 3). The primary parameters of the setup are:

❍ the time and frequency interval to be processed
❍ the *Z*-coordinate of the calculation plane

The selection of time and frequency intervals can be based on the time/frequency plot for a selected microphone signal. Here, the same array microphone as that used in the Raw Data view in Fig. 2 has been chosen, and the time/frequency interval selected for calculation is shown as a frame on top of the contour plot. The interval is seen to cover the time and frequency intervals of the first squeal. In addition, the calculation plane has been chosen close to the disc.

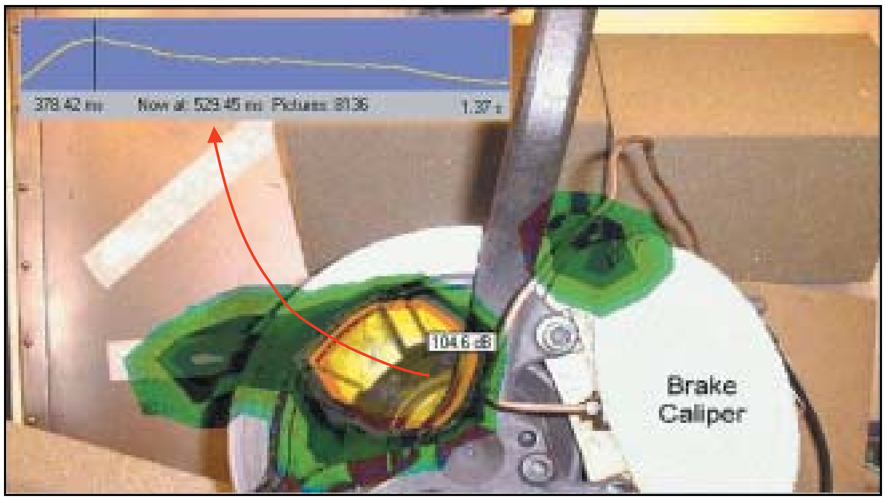


Fig. 4
Contour plot of Envelope Active Intensity. A time slice representing the position of the contour cursor is included. The contour interval is 1 dB

Fig. 4 shows a contour plot of the Envelope Active Intensity at the point in time where the peak value is highest. For the point in space where the peak occurs, the time slice of the Envelope Active Intensity is shown in the top, left-hand corner. The time variation is seen to be very slow over the 1-second interval of the calculated time-record. This is because the signal is so narrow-banded.

Surprisingly, the area of highest radiation is not over the disc itself, but on the less-rigid cover plate.

Analysing Microphenomena and Orders in Engine Noise Radiation

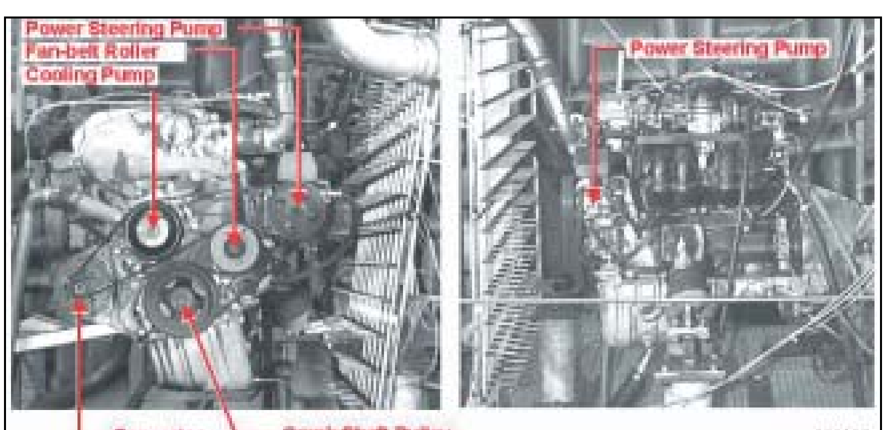


Fig. 5
Front- and left-side pictures of the engine also showing the array

Two series of measurements were taken over the front and left sides of a Daimler-Chrysler 2.3 litre engine (see Fig. 5). For all measurements, a sampling frequency equal to 8 Ksamples per second was used, supporting a frequency range up to 3.2 kHz. Each series included the following two recordings:

- Stationary 4000 RPM, Full Load, 2 s
- Run-up 1000–5400 RPM, Full Load, 10 s

The main purpose of the stationary measurements was to study the sound intensity map as a function of the crankshaft angle while that of the run-up measurements was to see the intensity map of the dominating orders at different RPM values during run-up.

The measurements were taken with a 12 × 10 grid of Array Microphones Type 4935, i.e., 12 rows and 10 columns. With a grid spacing equal to 7.5 cm, the supported frequency range extends to just over 2 kHz. The array size of 75 cm by 90 cm was sufficient to cover the major parts of the engine. Two tacho signals were recorded together with the array signals:

- one pulse per two rotations for definition of crank angle equal to zero
- two pulses per rotation for higher-resolution angle definition

First, look at the stationary, 4000 RPM measurement over the engine front with the purpose of studying the sound-power radiation as a function of crankshaft angle.

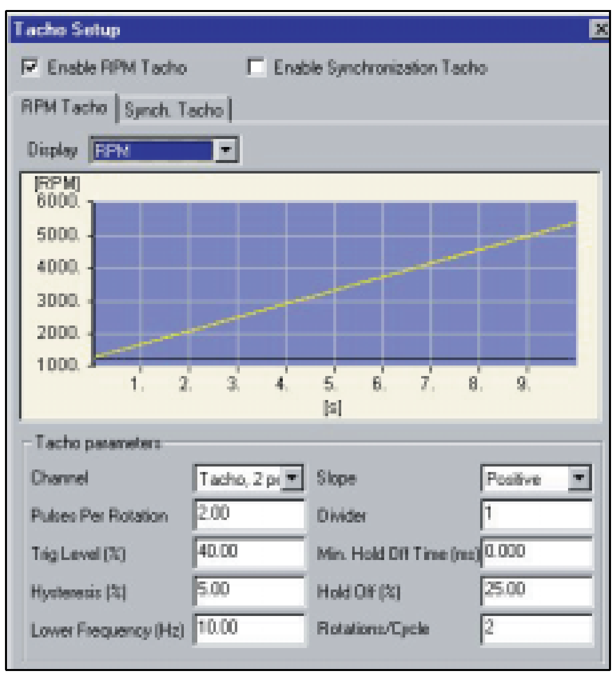


Fig. 6
Tacho Setup window

Fig. 6 shows the Tacho Setup window, where the signals to be used for RPM and crank-angle detection are selected and the parameters for the detection defined. The graphics area of the window can display the time signal, detected tacho sequence and RPM graph. In this case, the RPM graph has been selected.

Fig. 7
Bad Measurement Interpolation window

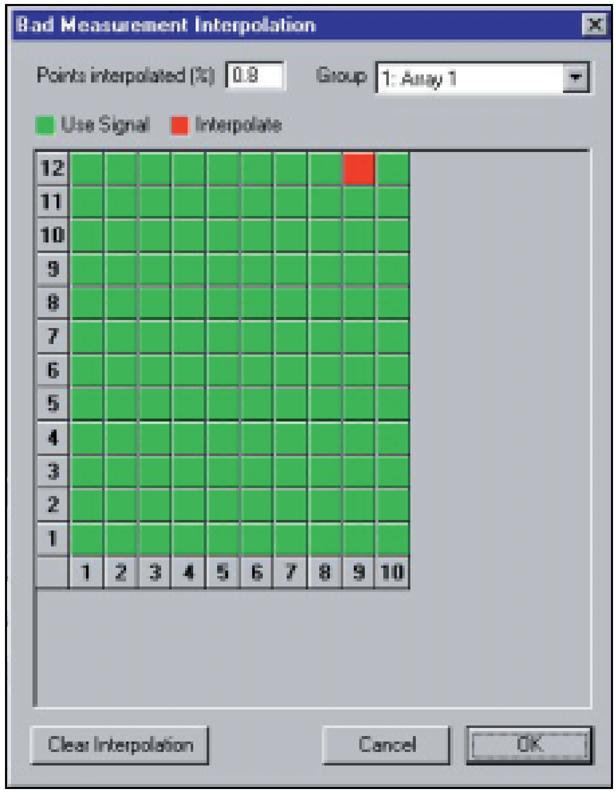
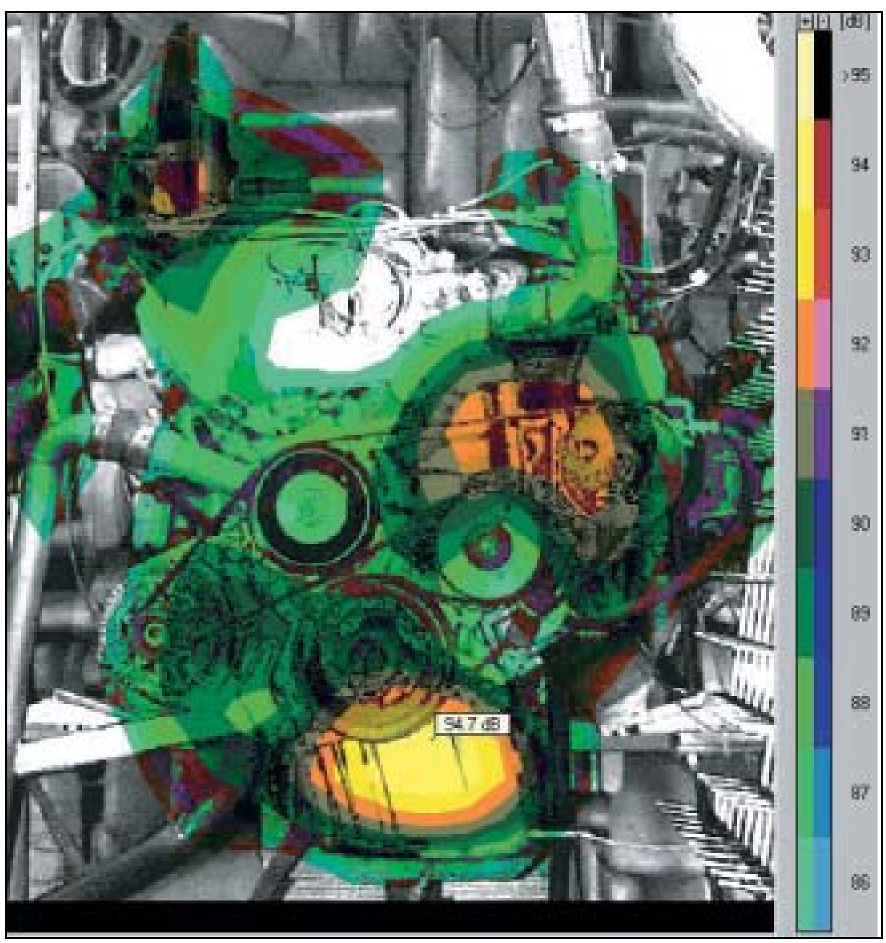


Fig. 8
Average Sound Intensity at the engine surface for the 1 kHz 1/3-octave band. The contour interval is 1 dB



During the analysis of the measured data for the engine front, it was discovered that the microphone in row 12, column 9 (by the upper right corner) had a bad connection; the measured signal was just impulsive noise. Fortunately, the Bad Measurement Interpolation function can be used to disregard the bad signal and replace it with interpolated data. Fig. 7 shows the menu for definition of array positions where measured signals are replaced by interpolated data.

A 1/3-octave filter was applied at 1 kHz, the sound intensity calculated over a plane at the surface of the engine, and averaged over 1 second. The resultant map of the Average Active Sound Intensity at the engine surface is shown in Fig. 8. The areas of highest radiation are seen to be just below the crankshaft pulley and around the upper part of the fan-belt roller.

In Fig. 8, all time or crank-angle resolution has, of course, been lost because of averaging. In order to obtain time or crank angle resolution, the averaging is skipped and the Envelope Active Intensity in the same plane at the engine surface calculated instead. The 1 kHz, 1/3-octave band of the stationary 4000 RPM measurement is also investigated.

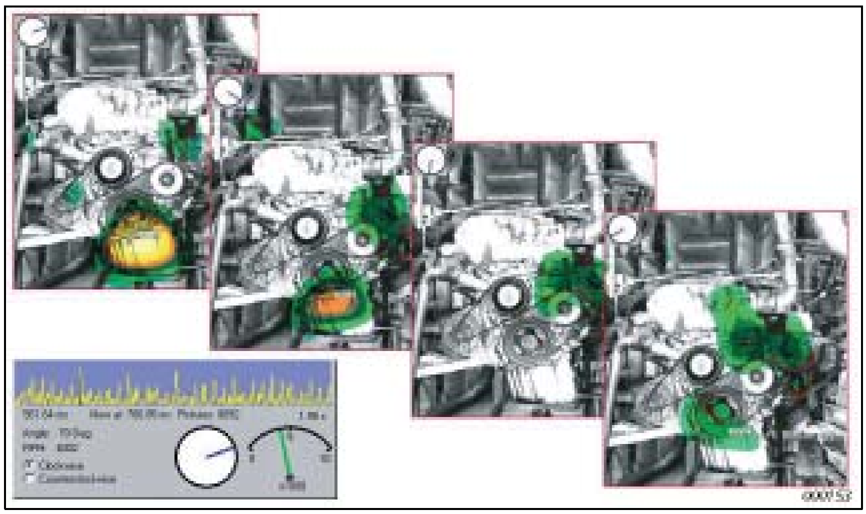


Fig. 9
Envelope Active Intensity at four different crankshaft angles and, below, the time slice at the contour-cursor position. Contour interval is 1 dB

Fig. 9 shows (from left to right) four snapshots with approximately 56° crank-angle interval – the crank angle being shown in the top left corner of each plot. A position cursor can be seen at the lower limitation of the crankshaft pulley and the Properties window below the sequence relates to that cursor position on the first plot in the sequence. The signal in the upper part of the Properties window is the (Envelope Active Intensity) time signal at the position cursor. Clearly, the signal at that position is very impulsive. A time cursor is seen in one of the impulses, indicating the instant in time represented in the contour plot. Looking again at the plot sequence, it can be seen that the impulse below the crankshaft pulley precedes the sound radiation from the area over and around the fan-belt roller. The impulse below the crankshaft pulley is probably due to the firing of the front cylinder. The cylinder pressure is transmitted through the crankshaft into the engine block from where noise is radiated. Subsequently, the deflection propagates to other parts of the engine. The high radiation around the fan-belt roller could be due to transmission through the timing belt.

At each instant in time, the Properties window also shows the RPM and the crank angle. The crank-angle indicators at the four instants-in-time represented in the plot sequence in Fig. 9 have been copied onto the four plots.

With the NS-STSF software, it is very easy to search in the time/position data and to perform time animations: by clicking at a point in time, the contour plot at that time will be displayed. By clicking at a position in the contour plot, the time data for that position will be shown in the Properties window. Animation is controlled by a standard set of playback controls. Several animations can be synchronised and run in parallel.

In Fig. 9, the time slice showed a certain, but not perfect, periodicity from cycle to cycle. If the aim is to obtain a good overview of the average radiation as a function of crank angle, then the time animation provides too much detailed information without giving the average picture.

To provide this overview, the NS-STSF software can perform averaging upon a set of Angle Intervals of specified equal width. For the engine front-measurement, a 10^o angular averaging interval-width was chosen, leading to a set of 72 intervals over the 720^o crankshaft rotation covered by a complete engine cycle.

Fig. 10 looks again at the Active Intensity in the 1 kHz, 1/3-octave band, but averaged in 10^o intervals. The two contour plots are identical, representing both the crank-angle interval around 50^o – only the cursor positions and the associated angle interval slices at the bottom are different. To the left, the contour cursor is over the oil sump, and the angle slice for that position shows that we are at the crank angle where the intensity over the oil sump is at its maximum. To the right, the contour cursor is above the fan-belt roller, but we still look at the crank-angle interval, where the oil-sump radiation peaks. The angle slice for the position above the fan-belt roller shows that the radiation at that position peaks a bit later than the radiation from the oil sump. Another difference is that the oil sump radiation is rather concentrated in angle, whereas the radiation around the fan-belt roller covers a rather broad crank-angle interval.

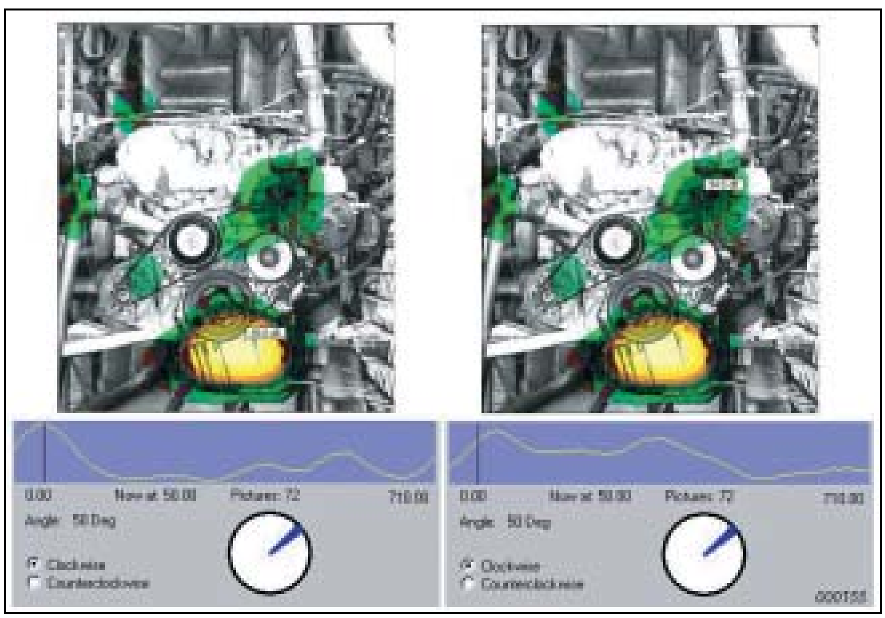
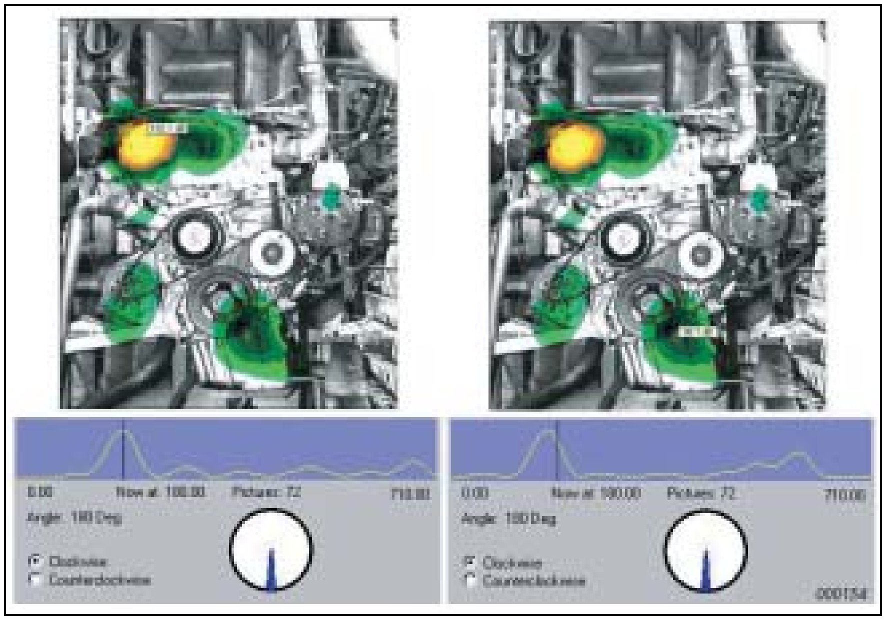


Fig. 10
1 kHz Active Intensity averaged over a 10^o crank angle 50^o after the firing of the front cylinder. The crank angle slices corresponding to the two contour cursor positions are seen at the bottom. Contour interval is 1 dB

This example illustrates the possibility of quickly reading the radiation versus crank angle at many positions by clicking the contour cursor at these positions, looking at the angle slice in the Properties window.

Fig. 11 presents the same comparison of the crank angle ‘timing’ of two hot spots of impulsive radiation, just for the 1.6 kHz instead of the 1 kHz, 1/3-octave band. Again, averaging in 10^o crank angle intervals has been used, but now the angle interval at 180^o is looked at, i.e., approximately half a crankshaft rotation after the firing of the front cylinder.

Fig. 11
1.6 kHz Active Intensity averaged over a 10° crank angle 180° after the firing of the front cylinder. The crank-angle slices corresponding to the two contour-cursor positions are seen at the bottom. Contour interval is 1 dB



In the left-hand view of Fig. 11, the contour cursor is over the valve cover, and the angle slice at the bottom indicates that the view is of the angle where the radiation from the valve cover peaks. Notice that most of the radiation is concentrated within a rather small angular interval. Fig. 11's right-hand view shows the same map (i.e., for the same crank angle) but the contour cursor is now over the oil sump. The angle slice for the radiation from the oil sump shows a peak before the angle cursor, i.e., before the peak radiation over the valve cover. The impulsive radiation from the oil sump apparently precedes the impulsive radiation from the valve cover.

We shall now look at the run-up measurements from 1000 to 5400 RPM with full load on the engine, starting with the measurement over the engine front.

A time/frequency analysis of the signal from an array microphone over the oil sump shows a very high level of the 13th order about 1 s before the end of the 10 s recording, (see Fig. 12).

Fig. 12
Time/frequency analysis of the signal from a microphone placed alongside the oil sump (red circle)

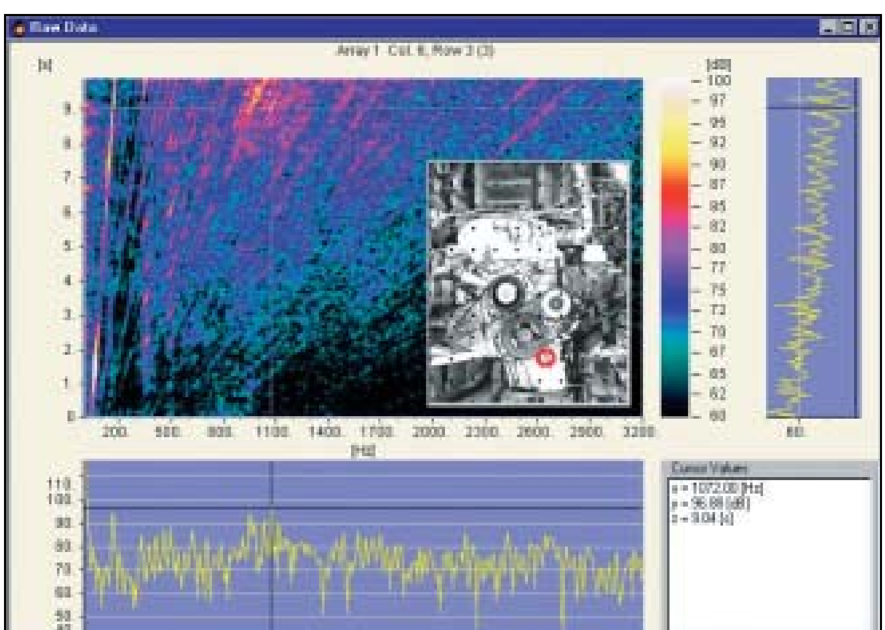


Fig. 13 shows the Calculation Setup window where the time and frequency intervals for the processing are selected. To facilitate this selection, we look at the same time/

frequency plot as in Fig. 12, where now the order interval between the 12.75th and the 13.25th order is shown on top of the plot. The rectangle represents the time and frequency intervals chosen for calculation – clearly the order band falls within the calculation window which covers the run-up from 2000 to 5400 RPM.

Again, the calculation plane is chosen to be at the engine surface.

In the Display Setup window, the order filter extracting the order interval from 12.75 to 13.25 is selected, as is the averaging of Sound Intensity in RPM intervals of 100 RPM width.

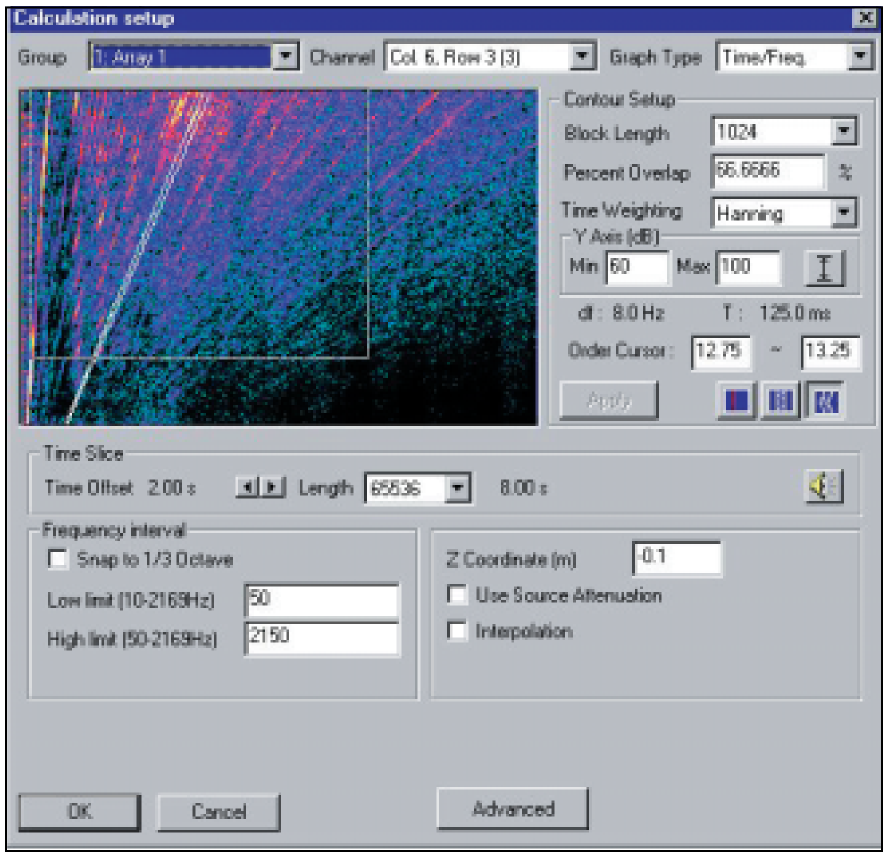


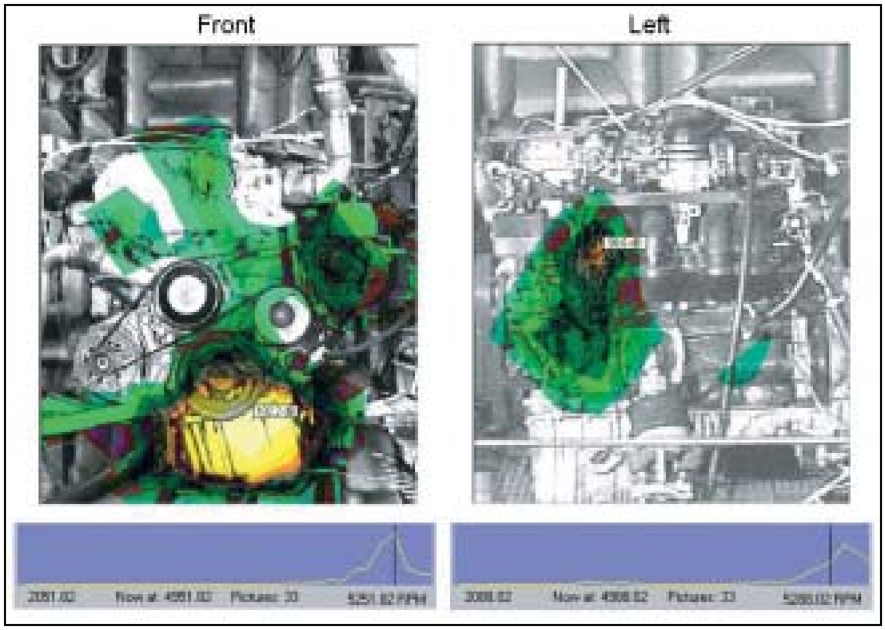
Fig. 13
Calculation setup used with run-up test

As a result of the holography calculation and the averaging, a sequence of contour plots of Active Intensity covering the set of RPM intervals of 100 RPM width from 2000 to 5400 RPM is obtained. This has been done for both the front measurement and the measurement on the left side.

The maps on the front and left for the RPM interval around 4950 RPM have then been selected. The Properties windows below the contour plots in Fig. 14 correspond to the cursor positions in these plots and show slices through the RPM intervals for these cursor positions.

The dominating peak on the front is seen to be over the oil sump and the contour cursor has been accordingly positioned. From the RPM slice under the contour plot can then be seen the RPM interval where the intensity level at the contour-cursor position has a sharp maximum. Looking at the contour plot, a smaller peak is seen between the power-steering pump and the engine block.

Fig. 14
Active intensity of 13th engine Order at the front and left sides of the engine. The intensity is averaged over an interval of width 100 RPM around 4950 RPM



The dominating peak on the left side of the engine (see Fig. 14) is between the power-steering pump and the air-intake manifold. From the RPM slice at that position, it can be observed that the level here is actually higher in the subsequent RPM interval, i.e., around 5050 RPM.

Conclusion

Using the NS-STSF system, the sound intensity, power, pressure, velocity and displacement maps from non-stationary noise sources can be obtained as a function of time, RPM, shaft angle or engine cycle in selected frequency or order bands. There is absolutely no restriction on the stationarity of the sound source – it can be anything from completely stationary to highly transient, e.g., as with a slamming door. All types of output data are available as time signals (with A/D converter sample rate) or averaged in time, RPM, shaft angle or engine-cycle intervals of user-specified width. Looking for the hot spots in time and space of transient sound-energy radiation, an overview is conveniently obtained by looking at a time-varying Envelope Active Intensity map.

Finally, all the above-mentioned information is available after a single, very fast, time-history recording with a simple microphone array.

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