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Crank Angle Analysis

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ABSTRACT

This paper describes the principle behind Crank Angle Analysis, as implemented by Brüel & Kjær in the Non-Stationary Spatial Transformation of Sound Fields (NS-STSF) system. The NS-STSF system combines a Time Domain Holography measurement on for example an engine with two simultaneously recorded Tacho signals. The Tacho signals provide the crankshaft angle and the RPM at the instant of each instantaneous output (snap-shot) from Time Domain Holography. As a result, the system allows precise analysis of the temporal and spatial relation between the acoustical emission (or the vibration pattern) and the mechanical events during an engine cycle. Some results from a measurement on a DaimlerChrysler engine are presented.

1. INTRODUCTION

Brüel & Kjær's Non-Stationary STSF (NS-STSF) system is an implementation of Time Domain Holography (TDH), [1]. TDH maps all sound field descriptors (pressure, particle velocity, intensity, etc.) in the near field, not only as a function of physical location, but also as a function of time. A TDH measurement can be seen as a sequence of snapshots of the instantaneous pressure over the array area, the time separation between subsequent snap-shots being equal to the sampling interval in the A/D conversion. Similarly, the basic output of TDH is a time sequence of snapshots of a selected acoustic quantity in a calculation plane parallel with the measurement plane. Sub-array scanning as used with Cross-Spectral Holography (implemented e.g. in STSF, [2]) can not be applied. A full-size two-dimensional microphone array with half wavelength microphone separation is needed.

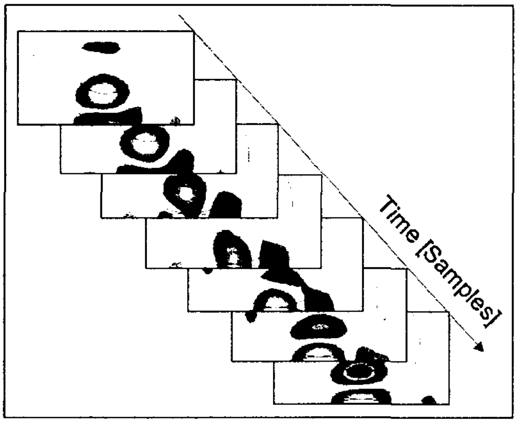

Fig. 1. *Illustration of the combined space and time resolution. The maps represent instantaneous air particle displacement over a plane at the sidewall of a tire. Green/Yellow colors represent outward deflection. Blue/Red colors represent inward deflection*

An example of output from TDH is given in Fig. 1, which contains a sequence of snapshots of Instantaneous Air Particle Displacement over a calculation plane at the sidewall of a truck tire.

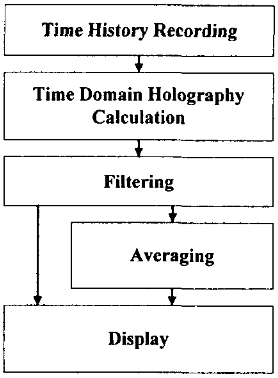

Fig. 2. *Data flow in NS-STSF*

Fig. 2 shows in schematic form the data flow in NS-STSF. Notice that averaging is optional – it is possible to display with sample rate time resolution. Sequences of maps can be animated, as illustrated in Fig. 1, to provide a visual understanding of the sound radiation process. Both Constant Bandwidth, Constant Percentage Bandwidth and Order filters are available. The CB and the CPB filters are implemented as windows in the temporal frequency domain without any phase shift. These filters therefore have no time delay, which can be important in connection with interval averaging in rather short time (or crankshaft angle) intervals.

When no averaging is performed, and the output is time signals, these signals can be exported to any type of post-processing. For example, exported pressure time signals can be used for subjective sound evaluation in the Brüel & Kjær PULSE Sound Quality software Type 7698.

2. TACHO SIGNALS

When NS-STSF is applied for engine noise analysis, two crankshaft tacho signals are normally recorded simultaneous with the array signals – one high resolution RPM Tacho for precise measurement of the crank angle rotation, and another once per cycle Synchronization Tacho for identification of a reference angular position, see Fig. 3. These two tacho signals allow the crank angle at the time of each snapshot to be identified in addition to the engine RPM. With the NS-STSF system it is therefore possible to visualize radiation and, at the same time, relate it to the different events during an engine cycle.

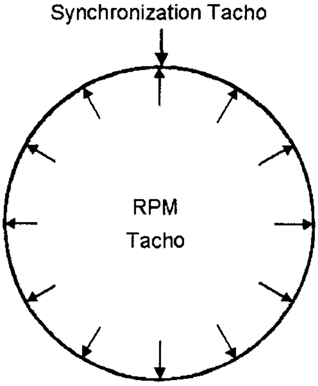

Fig. 3. Illustration of an engine cycle with indication of the high resolution RPM tacho and the Synchronization Tacho

3. INSTRUMENTATION

The microphone array consists of a large number of specially designed low-cost Brüel & Kjær Array Microphones Type 4935 that can be clipped into position in an open grid network. Fig. 4 shows an array with 10 columns and 12 rows of microphones fitted into a so-called Integral Connection Array Type WA0806 from. Here, the microphones do not need individual cabling. Instead, groups of six microphones are fitted into a tube with integrated cabling to a single LEMO connector, from where the six microphones are connected with a single cable to the front-end.

The front-end is a Brüel & Kjær Intelligent Data Acquisition (IDA) front-end system Type 3561. Time-history data is stored in real time in the front-end, and after the recording is completed, data is transferred through a standard Ethernet interface to the host computer running the Non-Stationary STSF software Type 7712. The IDA front-end can handle up to 3000 channels in multiple frames.

The software includes dedicated functionality to facilitate the handling of the large number of measurement channels often required for the NS-STSF application. For example, a Detect function automates the definition of the array (*row, column*) connections to the front-end channels (*frame, module,* and *channel*). Calibration can be performed on six microphones in parallel using a special pistonphone adaptor, and the system automatically detects which channels are being calibrated. Finally, there is extensive on-line monitoring of channel status, reporting for example cable break, CCLD (microphone preamplifier power supply) fault and Overload.

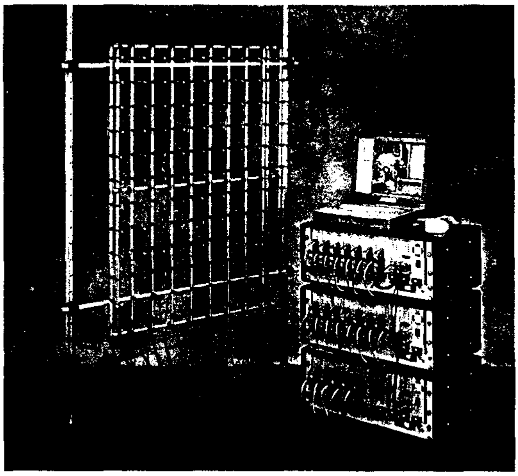

Fig. 4. 120 element microphone array, IDA front-end and computer for NS-STSF

4. ENGINE MEASUREMENT

An NS-STSF measurement was taken over the Front of a DaimlerChrysler 2.3 liter engine, see Fig. 5, where the array can be seen to the right. The array is actually the same as the one seen in Fig. 4. It has 12 rows and 10 columns with 7.5 cm grid spacing. We shall look at a stationary measurement, where the engine was running with full load at 4000 RPM.

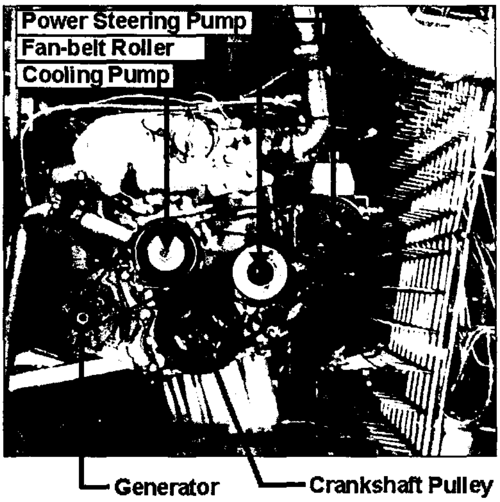

Fig. 5. Picture of the engine front with indication of some main components. The array is seen to the right.

The sampling rate was equal to 8K samples per second, providing a frequency range up to 3.2 kHz, and the recording time was 2 seconds. With 7.5 cm array grid spacing, the applicable frequency range extends up to a bit above 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: A Synchronization Tacho with one pulse per two rotations and an RPM Tacho with two pulses per rotation.

Fig. 6. *Average Sound Intensity at the engine surface for the 1 kHz 1/3-octave band. The contour interval is 1 dB*

We apply a 1/3-octave filter at 1 kHz, calculate the Sound Intensity over a plane at the engine surface and average over 1 second. As a result we get a map of the Average Active Intensity at the engine surface as shown in Fig. 6. 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. 6 we have, of course, lost all time or crank angle resolution because of the averaging. We therefore now skip the averaging and calculate instead the Envelope Active Intensity, [1], in the same plane at the engine surface. Still we look at the 1 kHz 1/3-octave band.

Fig. 7 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 so-called "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, indicating that a knocking type of sound could be radiated.

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, we observe 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 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.

During animation, the Properties window also shows the instantaneous RPM and the corresponding crank angle. The crank angle indicators at the four instants in time represented in the plot sequence in Fig. 7 have been copied onto the four plots.

561.64 ms Now at: 766.85 ms Pictures: 8092 1.55 s

Angle: 70 Deg
RPM: 4002
● Clockwise
○ Counterclockwise

Fig. 7. *Envelope Active Intensity at four different crankshaft angles and, below, the time slice at the contour cursor position. The contour interval is 1 dB*

With the NS-STSF software it is very easy to search in the time/position data and to perform time animations: By cursor 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 synchronized and run in parallel.

In Fig. 7 the time slice showed a certain but not perfect periodicity of the intensity from cycle to cycle. If the aim is to obtain a good overview of the average radiation as a function of crankshaft 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 into a set of Angle Intervals of specified equal width. For the present engine measurement we have chosen a 10° angular averaging interval width, leading to a set of 72 intervals over the 720° crankshaft rotation over a complete engine cycle.

In Fig. 8 we look again at the Active Intensity in the 1 kHz 1/3-octave band, but averaged in 10° intervals. The two contour plots are identical, representing both the crank angle interval centered at 50° - 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 much broader crank angle interval.

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.

The angular resolution obtained for example in Fig. 8 is limited by the frequency filter bandwidth through the length of its impulse response. As an example, better angular resolution will be obtained in the 1.6 kHz 1/3-octave band because of its larger absolute bandwidth.

5. CONCLUSION

Using the NS-STSF system, the sound intensity, power, pressure, velocity and displacement maps from rotating machines can be obtained as a function of time, RPM or crankshaft angle in selected frequency bands. The authors believe that valuable insight can be gained by the combination of crank angle resolution and spatial mapping provided by the system.

6. ACKNOWLEDGEMENTS

DaimlerChrysler is acknowledged for allowing us to use the Engine measurement.

7. REFERENCES

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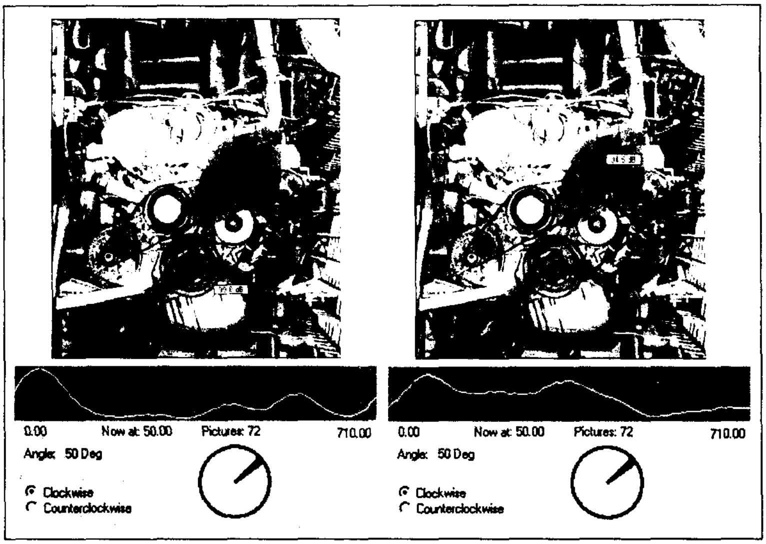

Now at: 50.00 Pictures: 72

Angle: 50 Deg

● Clockwise
○ Counterclockwise

Now at: 50.00 Pictures: 72

Angle: 50 Deg

● Clockwise
○ Counterclockwise

Fig. 8. 1 kHz Active Intensity averaged over a 10° crank angle interval 50° after the firing of the front cylinder. The crank angle slices corresponding to the two contour cursor positions are seen at the bottom. The contour interval is 1 dB