

Application Note

Tyre Noise Measurement on a Moving Vehicle

by Per Rasmussen and Svend Gade, Brüel & Kjær, Denmark

To obtain precise information about the noise radiation from tyres it is desirable to measure with the tyre in actual operation on a road. The STSF technique for tyre noise measurements is able to present detailed information about both the acoustical near-field, as intensity radiation mappings very close to the surface of the tyre, and far-field calculations such as pass by simulations and radiation patterns. Furthermore, by calculating the acoustic intensity vectors it is possible to establish an accurate relationship between the near-field and the far-field. The basic principle of STSF is to measure cross-spectra between a set of reference transducers and scan transducers covering a planar surface close to the sound source. These measurements result in a complete description of the sound field where both magnitude and phase are known at all points. By using mathematical techniques such as Helmholtz's Integral Equation and Near-Field Acoustic Holography, it is then possible to calculate acoustic quantities including sound intensity distribution, particle velocity, sound power, radiation pattern, etc. In addition, it is possible to simulate changes to the original sound source and predict, for example, the resulting far-field sound pressure level.



Fig.1 Microphone array positioning for tyre noise measurement on a moving vehicle

Introduction

Exterior noise from cars and trucks is made up of contributions from a number of dominating noise sources such as exhaust and air intake noise, power train noise, wind induced noise and tyre noise. Exterior vehicle noise is normally measured following the procedure in ISO standard 362 "Acoustics – Measurement of noise emitted by accelerating road vehicles – Engineering method" [1]. According to this standard, the noise is meas-

ured with a microphone placed 7.5 m from the center of the test road. The vehicle is accelerated past the microphone at full throttle and the registered noise level is the maximum level measured during the pass by. For the operational conditions encountered during a pass by test according to ISO 362, the dominating noise sources are normally the exhaust and air intake noise and the tyre noise. The noise from exhaust and air intake can often effectively be studied by making measurements on a rolling road inside a vehicle

semi-anechoic chamber, as for example described in Brüel & Kjær Application Note "Exterior Noise Measurements on a Rover 220 GSi" [2]. Measurements of tyre noise are, on the other hand, difficult to make on a rolling road, as the road surface is difficult to duplicate in the vehicle semi-anechoic chamber. The road surface for pass by noise measurements is specified in ISO standard 10844 [3] "Test surface for road vehicles noise measurements". This has precisely defined acoustical properties and results in a well-defined

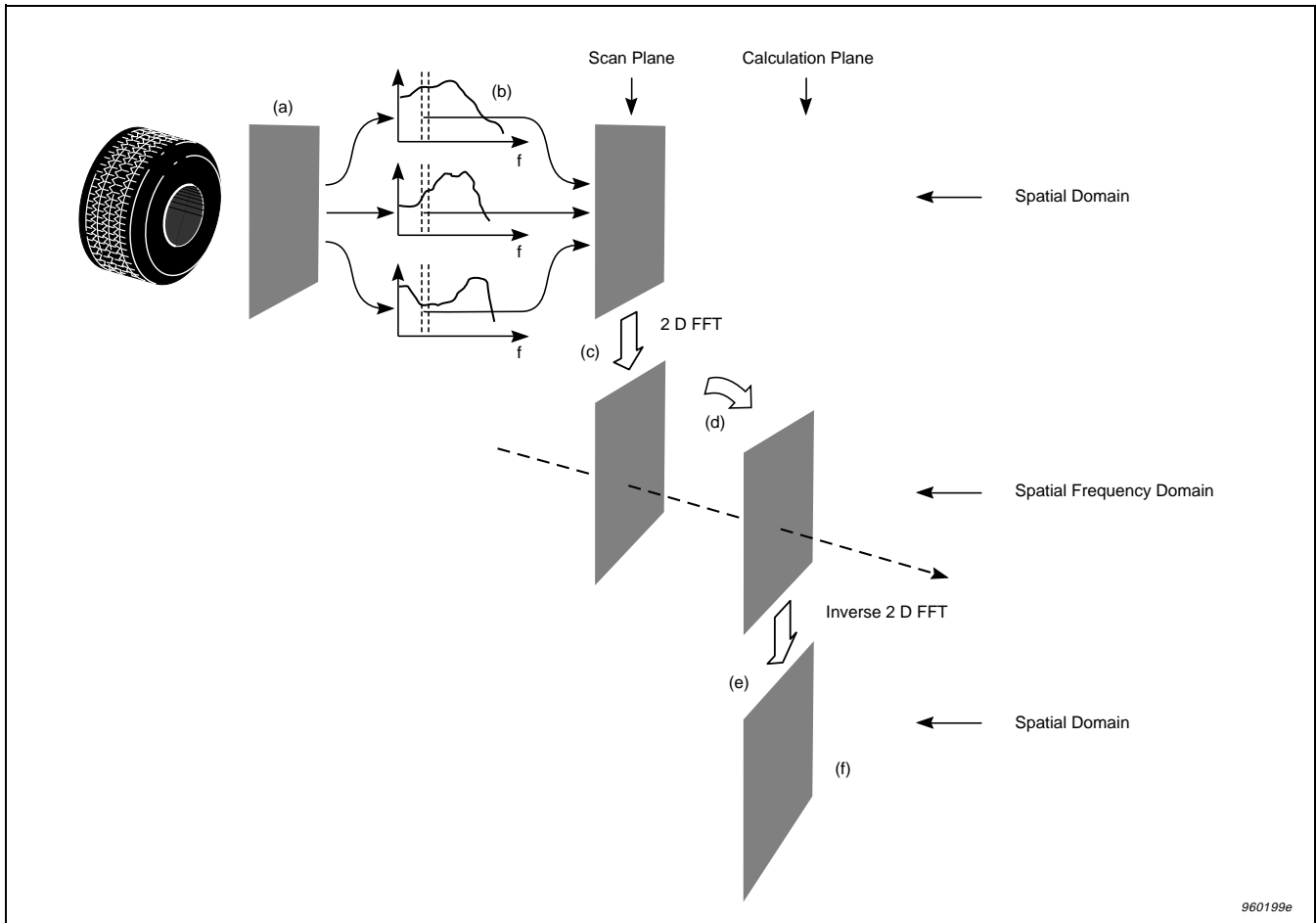


Fig.2 Overall principle of STSF; (a) measurement of cross-spectra in the scan plane; (b) calculation for one temporal frequency at a time; (c) 2D-spatial Fourier transformation; (d) transformation of simple wave types to other planes; (e) inverse 2D-spatial Fourier transformation; (f) to obtain the sound field in the new plane

noise generation from the road/tyre interface. The same noise generation is difficult to obtain on the rolling road, especially with the curved surface of the rolling road drum.

To obtain precise information about the noise radiation from tyres it is therefore desirable to measure with the tyre in actual operation on a road. By using the Spatial Transformation of Sound Fields (STSF) technique it is possible to obtain a complete description of the sound radiation from the tyre, including both near-field and far-field descriptors. The basic principle of STSF is to measure cross-spectra between a set of reference transducers and a set of scan microphones over a plane close to the sound source. These measurements results in a complete description of the sound field where both magnitude and phase of the sound pressure field are known at all points. By using mathematical techniques such as Helmholtz's Integral Equation and Near-Field Acoustic Holography, it is then possible to calculate acoustic

quantities including sound intensity distribution, particle velocity, sound power, radiation pattern, etc. In addition, with a computer it is possible to simulate changes to the original sound source and predict, for example, the resulting far-field sound pressure level.

STSF technique

The STSF technique is a combination of acoustic near-field calculations based on Near-Field Acoustic Holography and far-field calculations based on Helmholtz's Integral Equation, as described in detail by Jørgen Hald in Brüel & Kjær's Technical Review No.1, 1989, "STSF-A Unique Technique for Scan-Based Near-Field Acoustic Holography Without Restrictions on Coherence" [4]. A simple introduction to STSF can be found in [5], for example, but very briefly the overall principle of STSF can be simplified as in Fig.2. The sound field is

scanned in a plane close to the measuring object. This gives an array of spectra, one for each scan position. The spectrum at each position gives both the magnitude and the phase of the sound field at that position. Looking at a single frequency at all scan positions, a new array is generated containing the magnitude and phase information for one particular frequency. This array is spatially Fourier transformed in two dimensions, to generate a two-dimensional wave-number spectrum, which can be transformed to other planes, different from the actual measurement plane using simple transfer function operations. When the two-dimensional wave-number spectrum in the new plane has been calculated, an inverse Fourier transformation is used to obtain the pressure distribution in the new plane.

As opposed to a simple pressure mapping or intensity mapping of the sound field, the STSF system measures both the magnitude and phase of the sound field. This makes it pos-

sible to completely reconstruct the sound field mathematically. A simple analogy can be drawn between the sound field measurement and photographic techniques. Where a normal photograph records the magnitude of the light field on the film, a hologram records both the magnitude and the phase of the light field on the film. This makes it possible to completely reconstruct the light field as it existed when the hologram was recorded. Similar, as the STSF system records both the magnitude and phase, it is possible to completely reconstruct the sound field afterwards. The phase information of the sound field is obtained from a set of reference microphones distributed evenly over the scan area. See also Appendix A.

Measurements

The STSF measurements are performed with the instrumentation shown in Fig. 3. This consist of a microphone array, a multichannel data acquisition unit and a workstation with the STSF software. The array is mounted outside the car and the rest of the instruments, powered by a gasoline driven generator, inside the car.

The 6×6 microphone array was mounted on the side of the car, close to the right rear tyre, see Fig. 1. The size of the array was optimized to a frequency range from 450 Hz to 1 kHz. The upper frequency limit is determined by the spacing between the microphones in the array. In order to sample the sound field correctly, the array must have at least two microphone positions for each wavelength at the highest frequency of interest. At 1 kHz the wavelength of the sound waves is approximately 0.33 m. Thus a microphone distance of 0.15 m ensures two microphone positions for each wavelength. Similarly, the lower limiting frequency is determined by the overall size of the array. To measure the sound field correctly, the size of the array has to be equal to or larger than the wavelength of the sound. With a microphone spacing of 0.15 m and with 6 microphones in each direction, the array dimensions are 0.75 × 0.75 m. As the wavelength at 450 Hz is approximately 0.75 m, this is the lower limiting frequency.

The frequency range can be extended by decreasing the microphone spacing and increasing the array

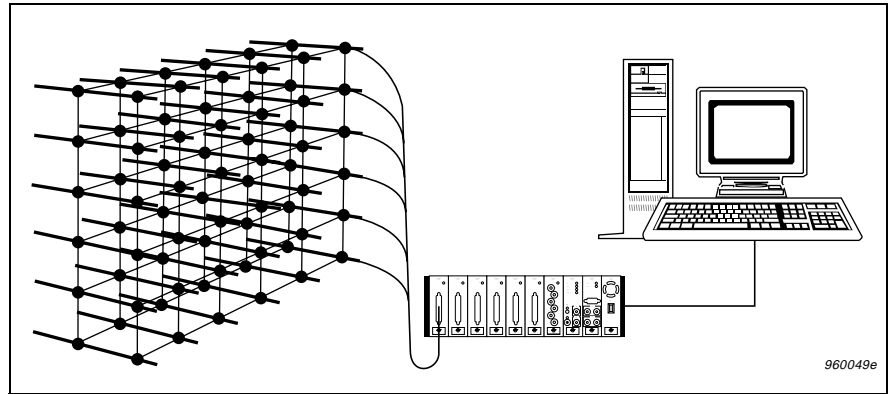


Fig. 3 STSF instrumentation set-up

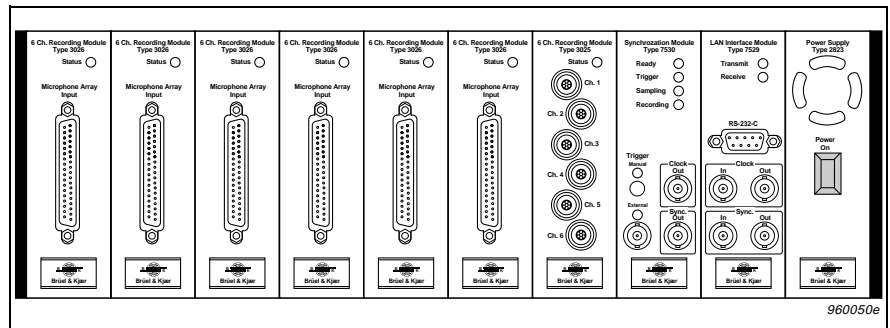


Fig. 4 42 channel IDA front-end

size, or alternatively by moving the array manually or automatically. In this way the frequency range can be extended up to approximately 7 kHz, while the lower limiting frequency, which can be obtained, is only limited by practical considerations about the physical size of the scan area.

Each of the array microphones is equipped with a small windscreen. The size of the windscreen is a compromise, so that the wind-induced noise on the microphones is minimal and at the same time the air flow around the array is not disturbed too much. Also the windscreen size has been selected so that the best performance is obtained in the frequency range where the tyre noise is dominant.

The reference microphones were equipped with larger and more effective windscreens than the array microphones. This is because, as long as the reference microphone signals are not disturbed by wind-induced noise, a certain amount of wind-induced disturbances can be tolerated on the array microphone signals. In principle, the STSF system only takes into account the part of the sound field which is coherent with the signals measured by the reference microphones. Wind-induced noise signals

from the array microphones will not be coherent with the reference microphone signals, and will therefore be excluded from the STSF calculations.

All the microphone signals are measured simultaneously with the Intelligent Data Acquisition (IDA) system. The IDA system consist of a number of 6-channel input modules, bundled together in frames with a synchronization module and interface units as in Fig. 4. Each IDA frame consists of up to 8 input modules, each with 6 channels, and a LAN Ethernet II interface module. Up to 64 of these frames can be connected together with a single synchronization module, which ensures that all datasampling in all channels is performed simultaneously.

The measurements were performed with the car coasting at approximately 80 km/hr. It was not possible to obtain higher speeds due to the limited length of the test road. The car was accelerated to slightly above the test speed, then the transmission was switched into neutral and the data acquisition was started. The total measuring time was 10 s, after which the measured data were transferred from the IDA system to the workstation for further processing.

Results

To check the integrity of the STSF calculations based on the measured data, the STSF system has a built-in validation function. This basically compares the calculated sound field with the actually measured sound field. Based on Near-Field Acoustic Holography, STSF can calculate the sound pressure in any plane closer to or further away from the measuring object. In particular, STSF can calculate the sound pressure in the scan plane. However, in this plane the actual sound pressure was measured during the scanning of the sound field, and the result of this measurement can be compared with the result of the calculations. Fig.5 shows a comparison of the actual measured sound pressure level at one of the microphone positions, compared to the sound pressure level calculated by the system. It can be seen that there is very good agreement between the measured and the calculated results. At low frequencies, i.e. below 500 Hz, the directly measured sound pressure level is slightly higher than the calculated. This is because the windscreens become less effective at low frequencies. As the calculated sound pressure level is based on only the part of the sound field which is coherent with the reference transducer signal, and this is not affected by the wind-induced noise.

Using Near-Field Acoustic Holography, the sound field close to the tyre can be calculated. The sound field can be described by the sound pressure, particle velocity or, as in Fig.6, by the sound intensity distribution over the surface. The sound field, measured 0.15 m away from the surface of the tyre, is projected from the measurement surface to the surface of the tyre. It can be seen that the major contribution, as expected, comes from the road/tyre interaction. The driving direction is indicated by an arrow in the upper right-hand corner, and it can be seen that the noise generation occurs at the leading edge of the tyre. Also there are two areas above this with a certain noise generation. This is most probably caused by turbulence from the array mountings.

The sound intensity generated by the road/tyre interaction is radiated to the far-field and the resulting sound pressure can be calculated us-

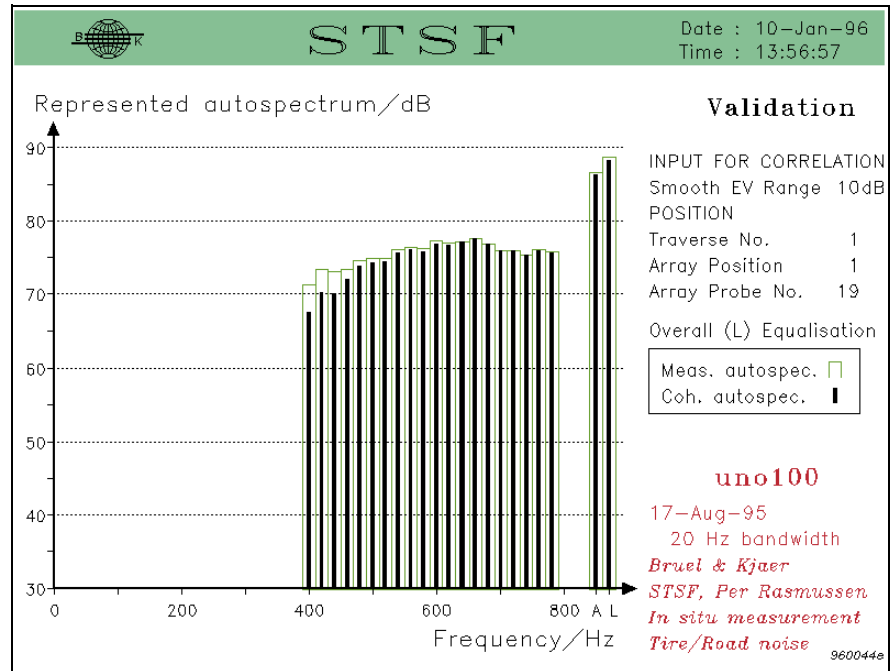


Fig.5 Validation, comparison of measured and calculated sound pressure at one microphone location

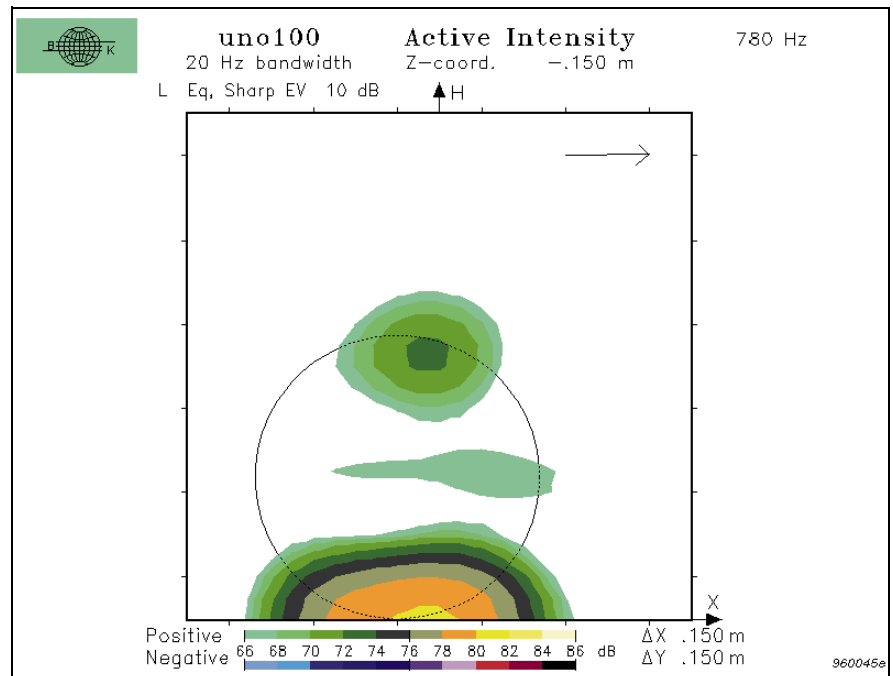


Fig.6 Sound intensity distribution at 780 Hz over the tyre surface

ing Helmholtz's Integral Equation. The sound pressure can be calculated anywhere within an angle of 90° from the measuring object and outwards. As an example the sound pressure, resulting from the noise radiated from the tyre is calculated at 7.5 m distance and at a height of 1.2 m, see Fig.7. These conditions corresponds to the situation of a

standard pass by test, only in the real pass by test the vehicle is traveling past a stationary microphone, while in this example this is accomplished mathematically, and for the noise from one tyre only. The sound pressure in the far-field shows a maximum 1.6 m in front of the line of symmetry. This indicates that the noise from the tyre is radiated for-

ward and not directly perpendicular to the car.

The sound intensity mapping in Fig.6 gives information about the acoustical near-field of the tyre, while the sound-pressure calculations in Fig.7 describes the acoustical far-field. By calculating the 3-dimensional intensity vectors of the sound field, the relationship between the near-field and the far-field can be described. The intensity vector maps in Figs.8a and 8b show how the acoustical energy generated by the road/tyre interaction is radiated away from the tyre. In Fig.8a, it can be seen that the sound intensity is radiated slightly forward, to produce the pressure maximum in front of the car, as in Fig.7. In Fig.8b, an additional radiation beam can be identified, radiating upwards at an angle of 45° from the road surface. This beam will not contribute to the sound pressure level at 7.5 m distance at the height of 1.2 m.

Conclusion

The STSF technique for tyre noise measurements is able to present detailed information about both the acoustical near-field, as intensity radiation mappings very close to the surface of the tyre, and far-field calculations as pass by simulations and radiation patterns. Furthermore, by calculating the acoustic intensity vectors, it is possible accurately to establish the relationship between the near-field and the far-field.

This measurement involved a single tyre and a reduced frequency range from 450 Hz to 800 Hz. By extending the microphone array, the frequency range of the STSF measurement can be extended to cover the full range of interest for tyre noise. Also, the measurement of the noise from the rear tyre should be complemented with a similar measurement of the noise from the front tyre. From each of the single tyre measurements the far-field result can be calculated and these results can then be added to obtain the pass by noise from the combination.

Appendix A: Theory

The STSF technique is a combination of acoustic near-field calculations

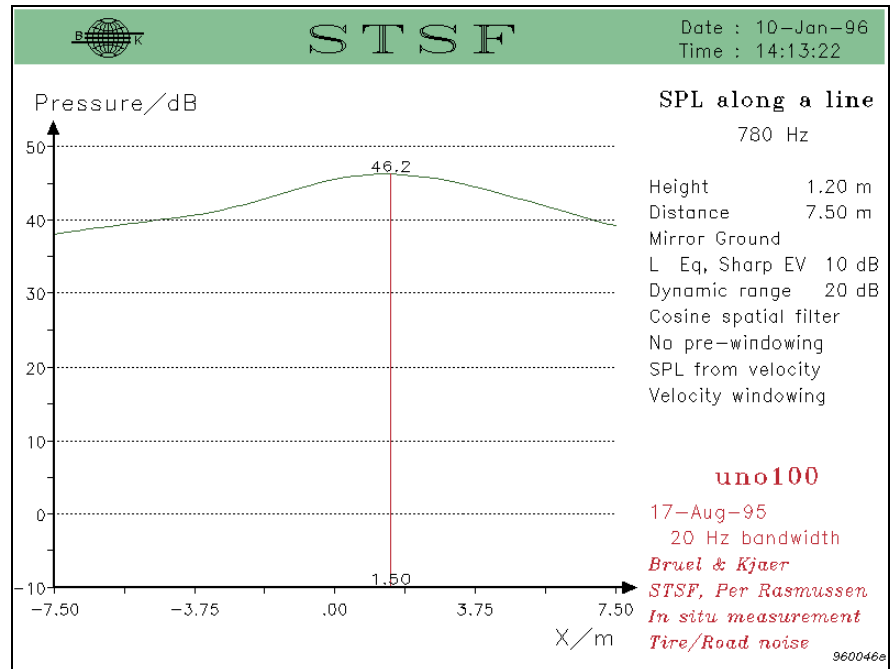


Fig.7 Sound pressure along a line at 780Hz, i.e. simulated pass-by test

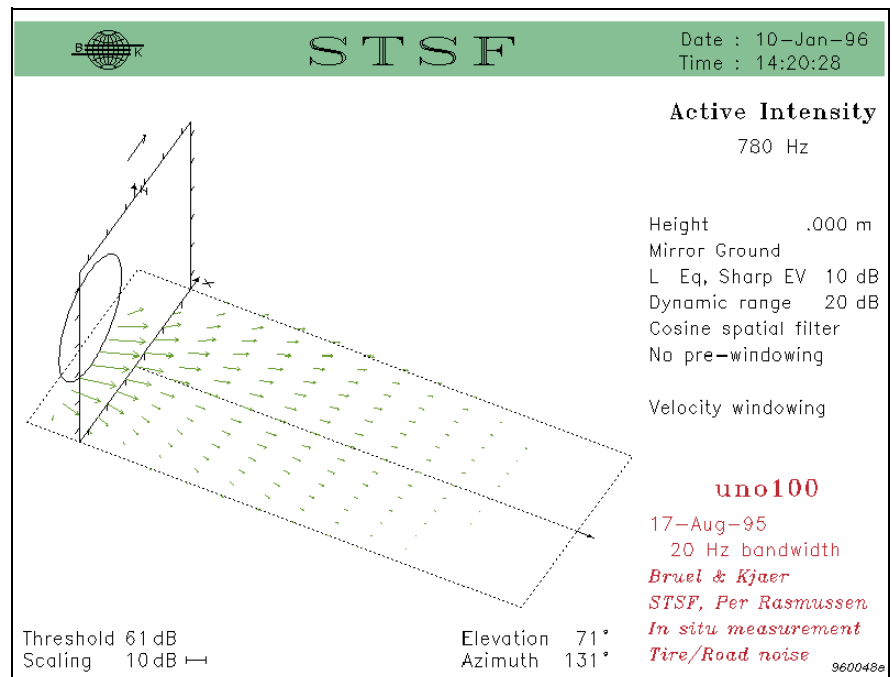


Fig.8a) Sound intensity vectors at 780Hz for indication of radiation pattern

based on Near-Field Acoustic Holography and far-field calculations based on Helmholtz's Integral Equation.

The basic assumption behind Near-Field Acoustic Holography is that the sound field can be decomposed into two simple wave-types: plane waves and evanescent waves. The plane waves describe the part of the sound field which is propagating away from the near-field towards the far-field and the evanescent waves describe

the complicated sound field existing in the near-field. Any sound field can be described as a combination of plane waves and evanescent waves with different frequency, magnitude and directions.

The magnitude and direction of the individual waves can be described by their spatial frequencies or wave numbers. For a simple plane wave propagating in a certain direction this can be described in terms of its

temporal frequency as well as by its spatial frequency. The temporal frequency, Fig. A1a is obtained by looking at the pressure changes with time at a certain point in the sound field. This gives the temporal frequency in Hz or rad/s. Similarly the spatial frequency, Fig. A1b is obtained by looking at the pressure changes at a certain time, the pressure will be different in different positions in space. If we move in a certain direction in space, we will see a certain change in the pressure, corresponding to a spatial frequency, measured with the unit cycles per meter or radians per meter. As the temporal frequency gives information about how often the pressure changes with time at a certain point, the spatial frequency gives information about how often the pressure changes with position at a certain time.

In the example of Fig. A1b, the propagation direction of the plane wave was identical to the direction of the axis along which we measure the spatial frequency, In this case, shown again in Fig. A2a, the relationship between the spatial frequency k_0 (i.e. the wave number) and the temporal frequency f is given by the speed of sound c :

$$k_0 = \frac{2\pi f}{c} = \frac{\omega}{c} = \frac{2\pi}{\lambda} \quad (A1)$$

where λ is the wavelength. If however, the axis along which the spatial frequency is measured is not the same as the propagation direction, see the example in Fig. A2b, this simple relationship is not valid. In this case, although the temporal frequency is the same as in Fig. A2a, the spatial frequency is lower.

For one particular temporal frequency, the spatial frequencies will thus give information about the propagation-directions. Therefore, if the sound field is made up of several plane waves, with the same temporal frequency, but with different propagation directions, this will be shown in the spatial spectrum as several spatial frequency components. If, for example, the sound field at one particular temporal frequency is a sum of two waves, Fig. A3, where one wave is travelling along the axis of measurement and the other at an angle of 45° relative to the first wave, the spatial spectrum will contain two spatial frequencies. One spatial frequency will be k_0 , corresponding to a wave in the direction along the axis

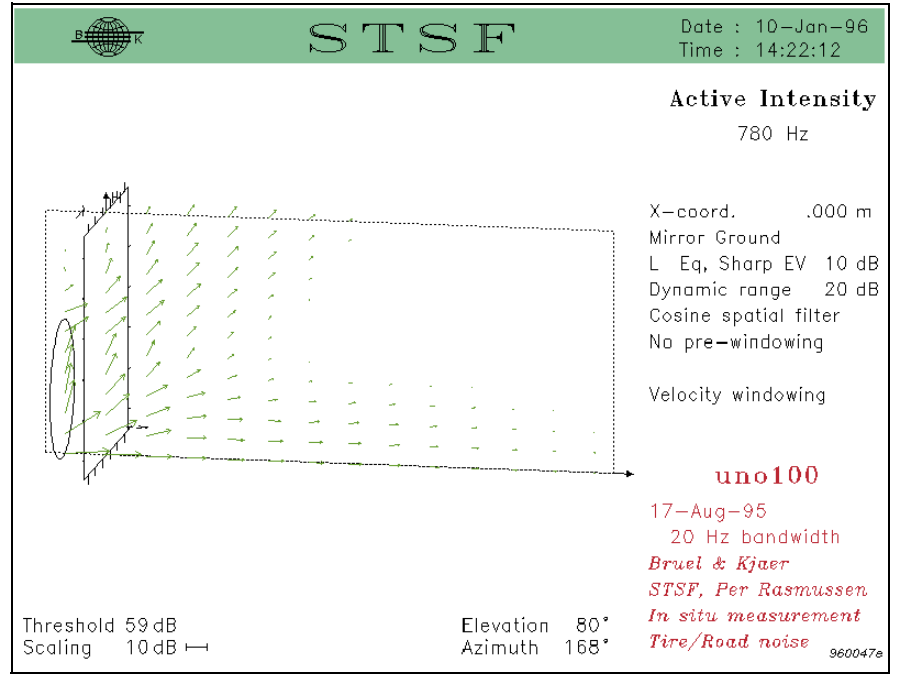


Fig.8b) Sound Intensity vectors at 780 Hz for indication of radiation pattern

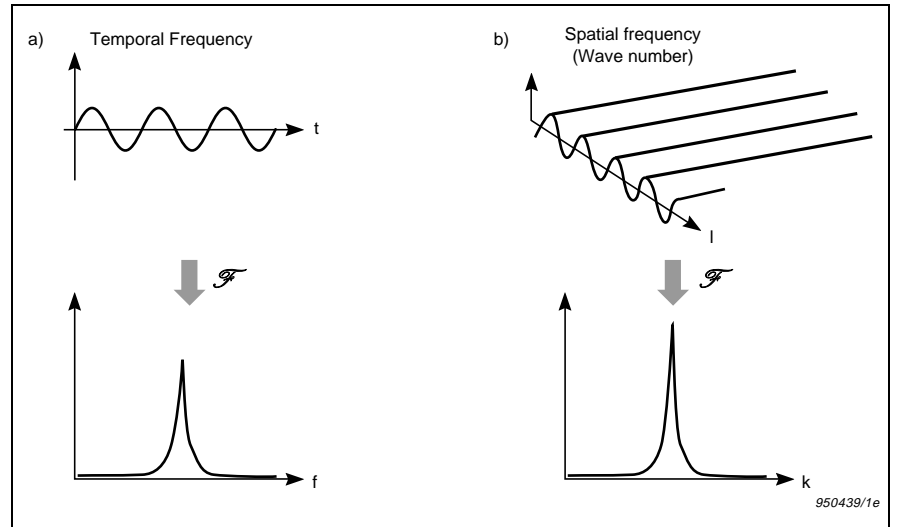


Fig.A1 Temporal and spatial frequency of plane wave

and the other frequency will be $k_0 \cos(45^\circ)$.

So far, the spatial frequencies have been defined along a single axis corresponding to a one-dimensional Fourier transformation. In the STSF technique, the sound-field is sampled not only along a single axis, but over a plane. Therefore, a two-dimensional Fourier transformation is used instead. This gives as a result a two-dimensional spatial frequency spectrum, but otherwise the information is the same as before: namely, infor-

mation about the direction and magnitude of the simple wave types. Fig. A4 shows an example of a two-dimensional spatial Fourier transformation. The sound-field, Fig. A4a, is from a point source in origin, radiating in all directions. The two-dimensional spatial Fourier transformation of the sound field in Fig. A4b, is a two-dimensional spectrum with a range of different spatial frequencies, corresponding to the fact that the point source is radiating in all directions at the same time.

The sound-field from the point source in Fig.A4a, cannot be explained by simple plane waves such as those in Figs.A2 and A3, as the amplitude decreases with the distance from the origin. The plane waves retain the same magnitude over the full plane. So to describe the near-field phenomenon, we have to introduce the evanescent waves. In the one-dimensional Fourier spectrum, the evanescent waves can be identified as spatial frequencies higher than $k_0 = 2\pi f/c$. Similarly, in the two-dimensional spatial frequency spectrum the evanescent waves can be identified as having spatial frequencies or wave numbers higher than k_0 . The spatial frequencies k in the two dimensional spatial spectrum can be calculated from the spatial frequencies k_x and k_y in the two directions.

$$k = \sqrt{k_x^2 + k_y^2} \quad (\text{A2})$$

Therefore, the spatial frequencies for which $k = k_0$ corresponds to a circle around origin with radius k_0 in the two dimensional spatial spectrum. This circle is called the radiation circle, as spatial frequencies inside this circle are radiated away from the near-field to the far-field, while spatial frequencies outside this circle are evanescent waves, i.e., they account for the complex sound field existing in the near field, but are not transmitted to the far-field.

Spatial frequencies less than k_0 are transmitted to the far-field and the amount of radiation is given by the wave number (or spatial frequency) k_z in the z-direction, perpendicular to the xy-plane. This can be calculated for each of the spatial frequencies from the equation:

$$k_z = \sqrt{\left(\frac{\omega}{c}\right)^2 - (k_x^2 + k_y^2)} \quad (\text{A3})$$

The individual spatial frequencies in the two-dimensional spatial frequency spectrum correspond to simple plane waves or evanescent waves in the scan plane, i.e. the measurement plane. For each of these simple wave types it is easy to calculate the pressures in other planes, see Fig.A5. For the plane waves (the spatial frequencies inside the radiation circle) a simple phase shift of the wave is required to calculate the result in a new plane. For the evanescent waves,

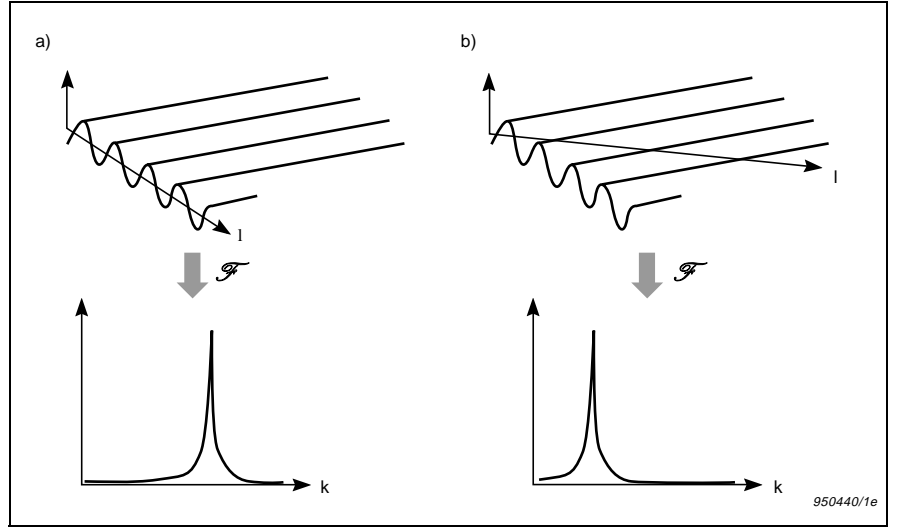


Fig.A2 Spatial frequencies of plane waves propagating in different directions

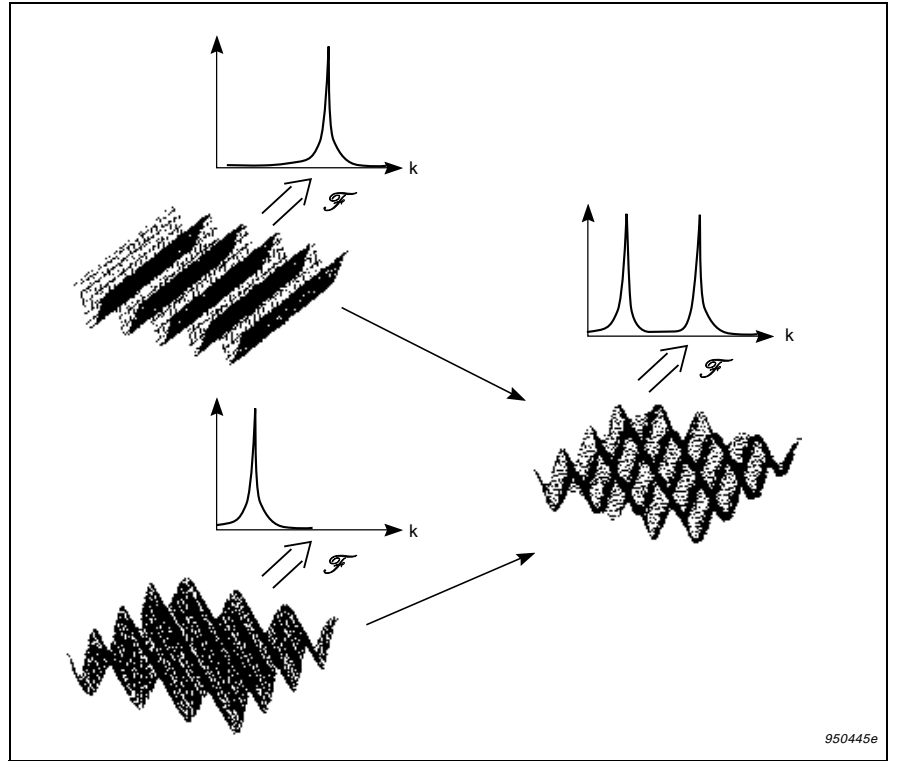


Fig.A3 Spatial spectrum of two plane waves propagating in different directions

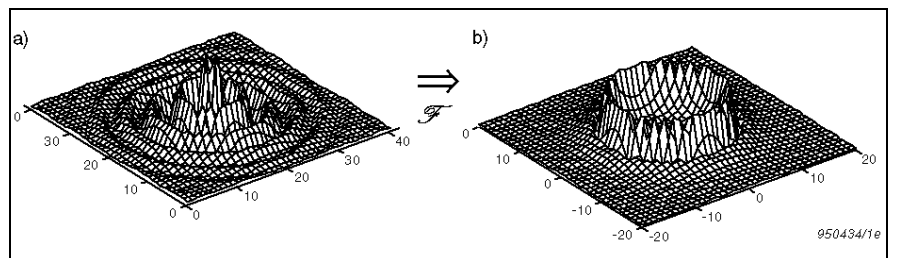


Fig.A4 Two-dimensional Fourier transformation of a sound field from a point source a) spatial domain b) spatial frequency domain

only changes in amplitude have to be taken into account, but in principle this is also a simple transfer function applied to the two-dimensional spatial frequency spectrum. In this way the two-dimensional spatial frequency spectrum in a new plane can be calculated from the original data by applying simple transfer function operations. The new two-dimensional spatial frequency spectrum is then a Fourier transform (in two dimensions) of the sound-field in the new plane.

The overall principle of Near-Field Acoustic Holography can be simplified as in Fig.2. The sound field is scanned in a plane close to the measuring object. This gives an array of (temporal) spectra, one for each scan position. Looking at one temporal frequency at a time, we take out the information from each of the spectra, corresponding to the actual frequency of interest. This generates a new array with information about only one temporal frequency. A Fourier transform (in two dimensions) is then applied to the array to generate a two-dimensional spatial frequency spectrum. This can then be transformed to the new planes using simple transfer function operations. When the two-dimensional spatial frequency spectrum in the new plane has been calculated, an inverse Fourier transform is used to obtain the new pressure distribution in the new plane.

In principle, the STSF technique requires that all the cross-spectra between all the scan positions are given, i.e., in each of the scan positions all the cross-spectra to all other scan positions must be determined. For a simple scan of a sound field with 25 times 40 scan positions, defining $N=1000$ scan positions would result in $\frac{1}{2}N(N+1) = 500500$ cross-spectra. Instead of measuring all these cross-spectra, the system uses a set of reference transducers to reduce the amount of cross-spectra. The number of necessary reference transducers to give a complete description of the sound field without measuring the full amount of data, is determined by the complexity of the sound field. A measurement with, for example, 4

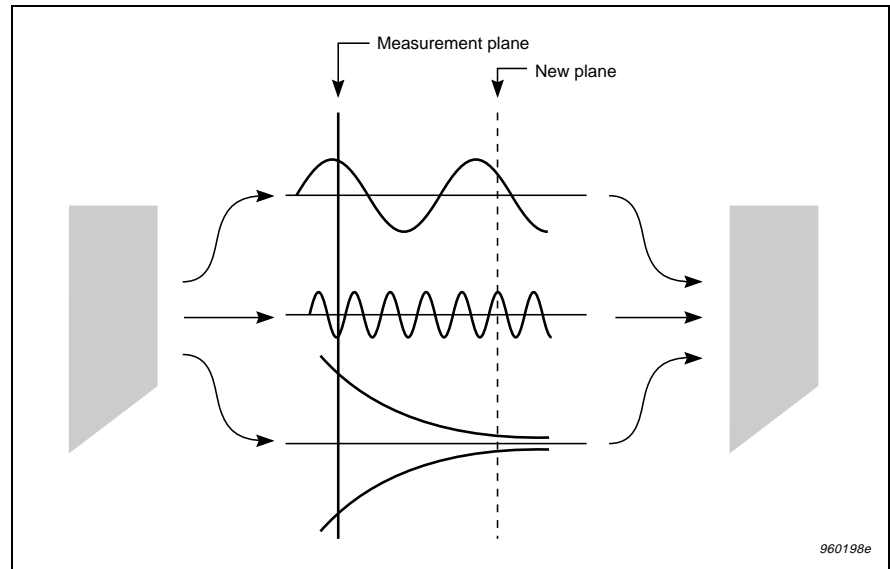


Fig.A5 Transformation of simple wave types at one temporal frequency in a spatial spectrum, from one measurement plane to another; two plane waves and one evanescent wave are shown

reference transducers and 1000 scan positions will then be reduced to $4N=4000$ cross spectrum measurements.

As indicated by the name Near-Field Acoustic Holography, the technique is used for calculating the acoustic quantities in the near-field of the sound source. To calculate the acoustic far-field the STSF system uses another technique, namely Helmholtz's Integral Equation, but based on the same data as Near-Field Acoustic Holography. Helmholtz's Integral Equation states that from a knowledge of the sound pressure and particle velocity distribution over a closed surface surrounding a noise source, the sound pressure can be calculated at any point outside the closed surface. This closed surface, which can be of any shape, is, in the STSF method, a hemisphere of infinite radius bounded by an infinite plane. Solving Helmholtz's Integral Equation with the measured scan data as input gives a set of transfer functions between the scan plane and the far-field. These transfer functions can then be used to calculate acoustic far-field quantities such as sound pressure level (SPL) or radiation patterns.

References

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Brüel & Kjær

WORLD HEADQUARTERS:

DK-2850 Naerum · Denmark · Telephone: +45 45 80 05 00 · Fax: +45 45 80 14 05 · Internet: <http://www.bk.dk> · e-mail: info@bk.dk

Australia (02) 9450-2066 · Austria 00 43-1-865 74 00 · Belgium 016/44 92 25 · Brazil (011) 246-8166 · Canada: (514) 695-8225 · China 10 6841 9625 / 10 6843 7426
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