Application Note

Measurement of Aerodynamic Noise using STSF

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Abstract

Until now it has been fairly difficult to measure accurately automobile aerodynamic noise in a wind flow using a microphone, because of disturbances such as the microphone self-generated wind noise and background noise in a wind tunnel.
This Application Note presents the results of checking the validity of the Spatial Transformation of Sound Fields (STSF) technique for noise measurements in a wind flow.
First, the basic validity is demonstrated by a measurement on a known source consisting of two loudspeakers and then the application of the method for automobile aerodynamic noise measurement is demonstrated.

Below, the interior of Honda's low noise wind tunnel. Above, the STSF scan array in use in the wind tunnel

1 Introduction

There are three major sources of noise inside cars: engine noise, tyrelroad noise and aerodynamic noise. The engine noise is currently being reduced by investing efforts in many noise reduction techniques. Therefore, the relative contribution of the aerodynamic noise to the interior noise under high speed driving conditions is increasing. To achieve further significant reductions in the interior noise, the aerodynamic noise must be reduced. Also, thinking about the environmental noise around highways, the external aerodynamic noise must be considered. Until now it has been difficult to measure aerodynamic noise using a microphone, primarily because the microphone generates noise itself. The cross spectral measurement technique applied in STSF can be used to reduce the influence of the self induced noise, and the holographic calculations of STSF can be used for precise localization of the turbulence noise sources from measurement taken outside the turbulence region.

2 Measurement Principle

2.1 Basic sound field transformation principles

The basic principle of STSF is to measure cross spectra of the sound pressure over a plane close to the sound source, and then apply Helmholtz'Integral Equation and Near-field Acoustic Holography to calculate descriptors of the sound field at other points. Helmholtz'Integral Equation is used for calculation of the Sound Pressure Level at rather large distances, while Near-field Acoustical Holography applies for calculation of pressure, particle velocity, active and reactive acoustic intensity in the near-field region, both closer to and further away from the source than the measurement plane (Fig. 1).

In Near-field Acoustic Holography the spatial distribution of (complex) pressure on the measurement plane z=O is transferred to the spatial frequency domain using a two-dimensional FFT. (Fig.2). The spatial frequency domain representation can then be easily "moved" to a parallel plane **z=z'** by multiplication with a transfer function, and the acoustic field reconstructed by taking the inverse two-dimensional FFT.

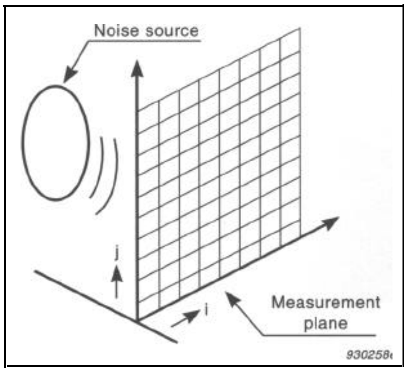

Fig. 1 Noise source and measurement plane

Fig. 3 illustrates the use of the spatial frequency domain in the holography calculations. Plane waves and evanescent waves in the spatial domain are located inside and outside respectively of the so-called radiation circle in the spatial frequency domain. The evanescent waves contain the high resolution information and therefore the capability of precise localization of noise sources. In order to pick up as much as possible of the evanescent wave information, the measurement plane must be as close as possible to the sound source.

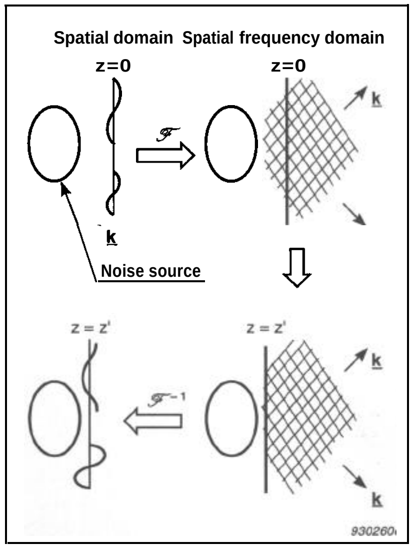

Fig. 2 Principle of Near-field Acoustic Holography

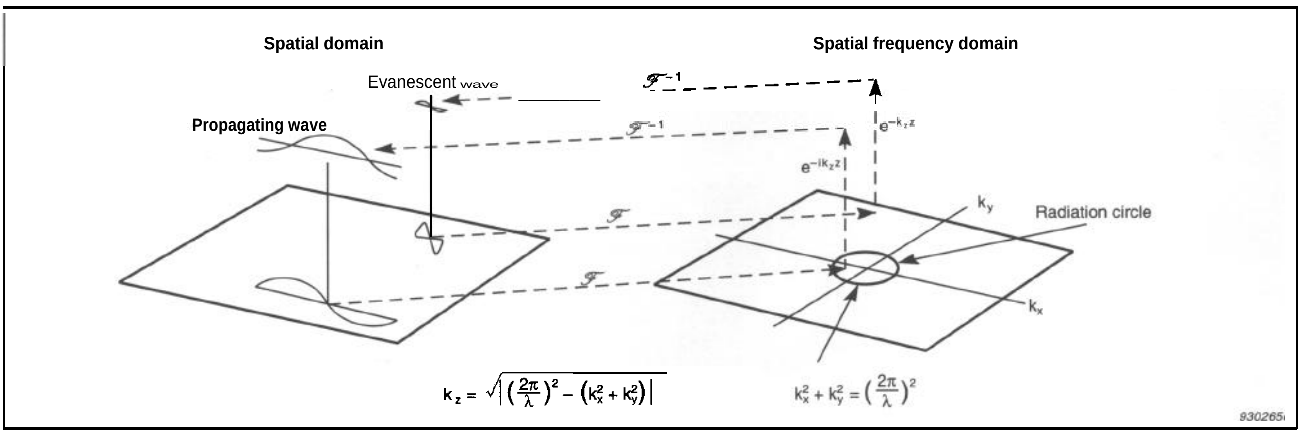

Fig. 3 Relationship between spatial domain and spatial frequency domain

2.2 The cross spectral measurement technique

In the general case where no assumptions are made about the coherence of the sound field, the cross spectrum must be measured between every pair of measurement positions in the scan plane in order to obtain a complete cross spectral model of the sound field. For example, with N rows and N columns of measurement positions, the number of cross spectra to be measured will be N^4.

But in STSF the noise source is assumed to have only a limited number (q) of independent parts. Under this assumption we need only measure the cross spectrum from every position to each of a set of q references (scan measurement) and the cross spectrum between every pair of references (reference measurement).

In this case we need to measure only $qN^2 + q^2$ cross spectra which is a very significant reduction when q is small (Fig. 4)

In order to avoid the need for simultaneous measurement of all cross spectra, the source is assumed to be stationary stochastic, and all positions are covered by traversing a column array or a single microphone across the measurement area (Fig. 4).

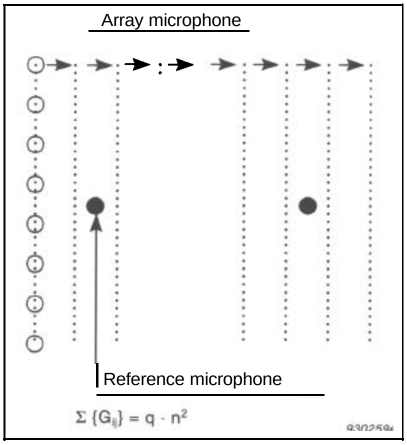

Fig. 4 Reduced cross spectral measurement

2.3 Rejection of wind noise generated by the microphones

In general it is difficult to measure aerodynamic noise generated by the surface of a car using a microphone located in the flowing air because the microphone itself generates noise even when a wind shield is applied. The cross spectral measurement technique applied in STSF provides a means of reducing the self generated noise. Provided the reference transducers are not in the flow (and thus do not generate noise) and provided they do not pick up the noise generated by the scan microphones, then this self generated noise will be averaged out in the cross spectra between the references and the scan microphones. This is described mathematically in the following. We shall apply the symbols defined below:

- P_R total reference microphone signal
- P_A total array microphone signal
- P_{RW} aerodynamic noise part of reference signal
- P_{AW} aerodynamic noise part of array microphone signal
- P_{RM} wind noise generated by array microphones and measured by a reference microphone
- P_{AM} wind noise generated by array microphones and measured by an array microphone
- P_{RB} background noise measured by reference microphone
- P_{AB} background noise measured by array microphone

Here, the total microphone signals can be written as

$$P_R = P_{RW} + P_{RM} + P_{RB} \qquad (1)$$

$$P_A = P_{AW} + P_{AM} + P_{AB} \qquad (2)$$

The cross spectra applied in the STSF technique are the cross spectra G_{RR} between the references, and the cross spectra G_{RA} between reference and array microphones. If we want to remove the influence of the self induced wind noise from the STSF model of the sound field, it is important to avoid the generation of wind noise in the references, because this kind of noise will contribute to the reference auto-spectra G_{RR}. We shall therefore assume that the references are outside the air flow and thus do not generate significant wind noise.

Denoting by "*" a cross spectrum operation between two signals, the cross spectra G_{RR} can then be expressed as

$$G_{RR} = P_R * P_R$$

$$= (P_{RW}+P_{RM}+P_{RB})*(P_{RW}+P_{RM}+P_{RB})$$

$$= P_{RW}*P_{RW}+P_{RM}*P_{RM}+P_{RB}*P_{RB} \qquad (3)$$

where we have assumed that aerodynamic noise, self induced noises and background noise are mutually uncorrelated. Clearly, the wind noise P_{RM} created by the array microphones must be negligible compared to the aerodynamic noise P_{RW}, at the reference microphones and it can then be disregarded in eq. (3). If the reference microphones generate wind noise, this noise must also be small compared to P_{RW}. In the Honda wind tunnel, the background noise is very low (less than 60 dB(A), see Fig.5), and it can therefore be disregarded. Consequently, we obtain from equation (3)

$$G_{RR} \approx P_{RW}*P_{RW} \qquad (4)$$

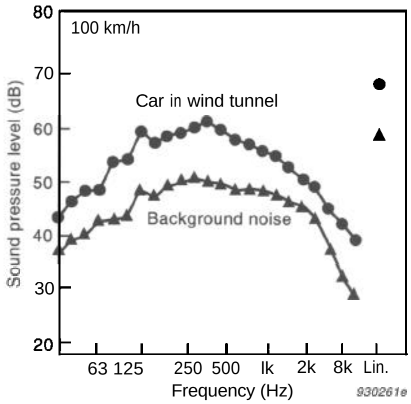

Fig. 5 Background noise level in wind tunnel

For the cross spectra G_{RA} between references and array microphones we obtain similarly

$$G_{RA} = P_{RW}*P_{AW}+P_{RM}*P_{AM}+P_{RB}*P_{AB} \qquad (5)$$

For the same reasons as above, we shall disregard the contribution from the background noise:

$$G_{RA} \approx P_{RW}*P_{AW}+P_{RM}*P_{AM} \qquad (6)$$

However, the wind noise generated by the array microphones will normally have a very high level as measured by one of the array microphones because a turbulence source is just in front of the microphone. In order that the second term in eq. (6) can be neglected, the same array wind noise must be very small as measured by the reference microphones. Effectively, the following inequality must hold

$$|P_{RM}*P_{AM}| << |P_{RW}*P_{AW}| \qquad (7)$$

in order that we can obtain the desired expression

$$G_{RA} \approx P_{RW}^{*}P_{AW} \quad (8)$$

The undesired array wind noise contribution to the cross spectrum G_{RA} can be reduced by selecting optimum sized and shaped wind screens on the array microphones, by the use of only a single array microphone and by positioning the references as far as possible from the array. The desired aerodynamic wind noise contribution to the same cross spectrum can be maximized by positioning the references as close as possible to the aerodynamic noise sources and by scanning the array as close as possible to these sources.

Positioning of the references close to the noise sources of interest will in general reduce the influence of other undesired sources.

Although one scan microphone is the best solution as far as only the suppression of self induced noise is considered, an array of scan microphones is chosen in order to reduce the measurement time. By the use of a rather large spacing in the array, the noise from the other microphones at a given array microphone position can be minimized.

3. Measurement system

Fig. 6 shows the configuration of the measurement system. A car is located in the low-noise wind tunnel. Several reference microphones can be set up inside and/or outside the car. A vertical array of microphones with small wind shields are scanned along the side of the car. Both the reference and the scan microphones are pressure microphones connected to a Brüel & Kjær Dual Channel Real Time Analyzer Type 2133 through Brüel & Kjær Type 2811 multiplexers. Analyzer, multiplexers and a microphone traversing system are controlled by a HP9000 series computer. During the scan of the microphone array, a cross spectral model of the sound field coherent with the reference signals is acquired.

Afterwards, this model can be used for mapping of sound pressure level, (active and reactive) sound intensity and sound power.

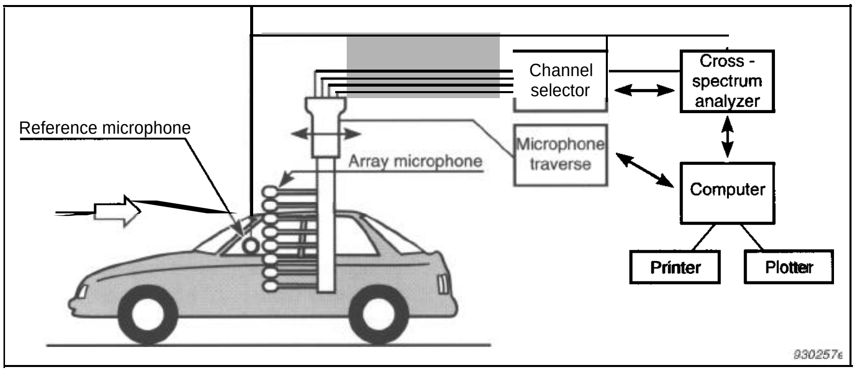

Fig. 6 Configuration of measurement system

3.1 Selection of wind shields

A series of measurements were taken over a loudspeaker sound source in a wind flow in order to identify the best way of reducing the self induced noise picked up by the array microphones. In order to avoid too much influence of the array on the air flow in the measurement region, it is very important to keep the dimensions of wind shields small. The standard Brüel & Kjær wind-screens were too large, and therefore a set of smaller screens were made and their noise reduction was compared with that of other typical shielding methods.

Fig. 7 shows the array with its carriage structure and with the small wind-screens fitted on the microphones. Fig. 8 shows the test setup for wind-screen selection and the results are presented in Fig. 9. The cross spectrum between the loudspeaker excitation signal and the signal from the array microphone is measured with a finite averaging time of 4 seconds with and without wind flow. The best windshield will give the smallest deviation between .the two cross spectra.

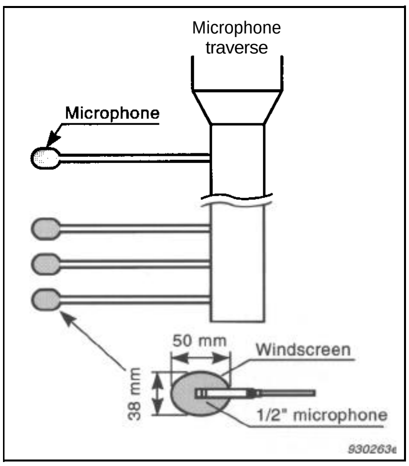

Fig. 7 Microphone array with windscreens

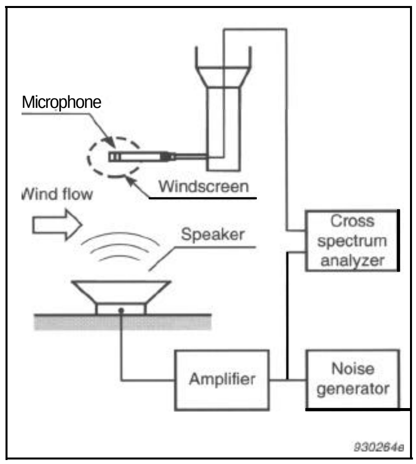

Fig. 8 Test setup for windscreen selection

Two distinct cases are considered in Fig. 9:

(a) steady state wind flow
(b) turbulent wind flow

In both cases a wind speed equal to 100 km/hour was applied. In case (b) the microphone was placed in the turbulent flow behind a side mirror of a car.

Three different shielding methods are investigated:

(1) small wind-screen
(2) nose cone
(3) no wind shielding

For the case of steady state wind flow (a), the cross spectral averaging is almost sufficient to suppress the self induced noise with all three shielding methods. The small wind-screen is, however, the best. For the case of turbulent wind flow, only the small wind-screen provides acceptable results – within approximately 1dB from the measurement with no wind flow.

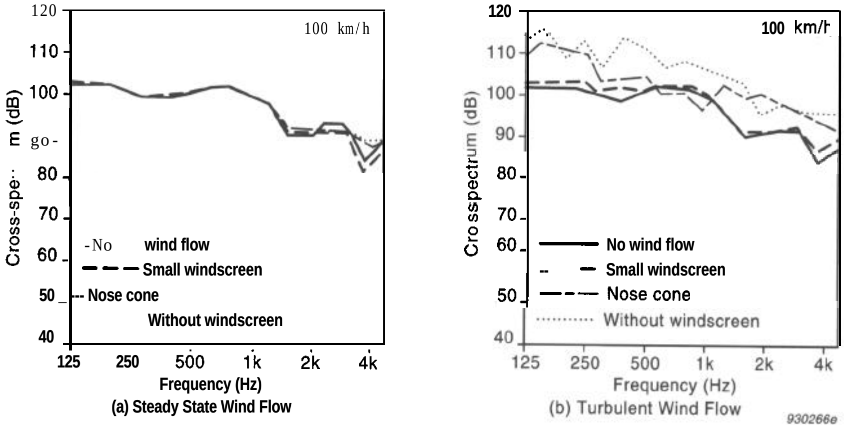

Fig.9 Test results of windscreen selection

4. Verification of the Measurement Technique by a Loudspeaker Measurement

4.1 **Verification method**

It is impossible to verify the ability of STSF to identify noise sources in a wind flow by taking measurements on aerodynamic noise sources, because the localization of these noise sources and their acoustic power are unknown. Instead, we shall compare two measurements on a set of loudspeakers: one with wind flow and one without.

Fig. 10 shows the experimental set-up. Two loudspeakers excited by pink noise are located one after the other in the flow direction.

The sound pressure level from the speakers is adjusted to equal the aerodynamic noise level just in front of the speakers, and the electric signal from the generator is used as reference signal. This signal has high coherence with the sound field from the loudspeakers and no coherence with the wind induced noise. The scan array consists of 8 microphones with 56 mm spacing. The distance from the loudspeakers to the scan plane is 100 mm and the height of the loudspeakers above the floor is relatively large to approximate free-field conditions in the measurement region.

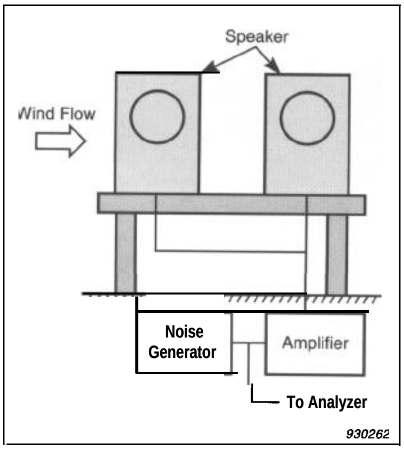

Fig. 10 Speaker test setup

4.2 Results of the verification

Fig. 11 shows the calculated acoustic intensity distribution on the surface of the loudspeakers. The two plots show good agreement between the case with presence of wind flow and the case without wind flow. The sound intensity levels in front of the loudspeakers agree within ± 1 dB with and without wind flow, indicating that noise sources can be localized and quantified with high accuracy in a wind flow.

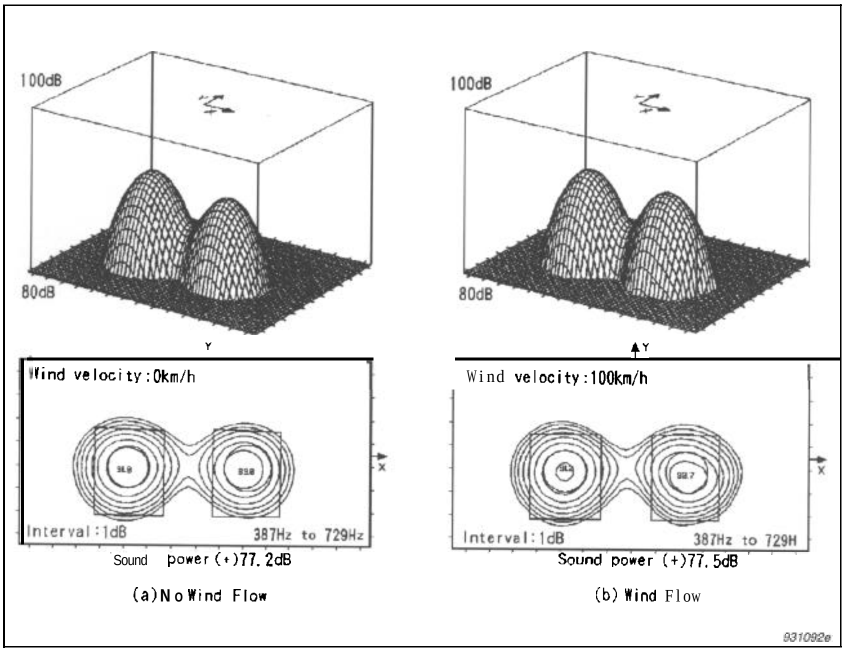

Fig. 11 Sound intensity distribution

5. Application for Automobile Aerodynamic Noise Measurement

5.1 Measurement set-up

The vehicle is fixed on the turntable in the wind tunnel, and the vertical linear microphone array is moved along the side of the vehicle.

The distance from the centre of the side window to the scan plane is 250 mm. Eight microphones with 112 mm spacing constitute the array, which is scanned from the front of the vehicle to the rear in 112 mm steps. Two sweeps (traverses) are performed to cover the vertical extent of the scan area. A sound pressure microphone located at a typical ear position of a passenger, 100 mm from the side window, is used as reference.

Since the floor is perfectly reflective, a mirror ground type of measurement is selected, with the lowest scan microphone very close to the floor.

5.2 **Results**

Fig.12 and Fig.13 show the pressure distribution on the surface of four different vehicles. Although the NAH calculations require a homogeneous source free medium between the measurement plane and the calculation plane, reasonable results are achieved because the inhomogenities are either small or correspond to rather small deviations from the homogeneous average. Small inhomogenities will cause a distortion (blurring) of the pressure map, while sources between the measurement and calculation planes will be reproduced in a defocussed form.

The pressure level is high behind the side mirror and behind the front tyre. Otherwise it is low. These regions with high pressure coincide very well with the region where flow rejoins the car body after a separation.

Recall that the mapped sound field is the part of the total sound field which is coherent with the reference signal. Therefore, Fig.12 and 13 show the pressure field which is coherent with the sound perceived by the passenger.

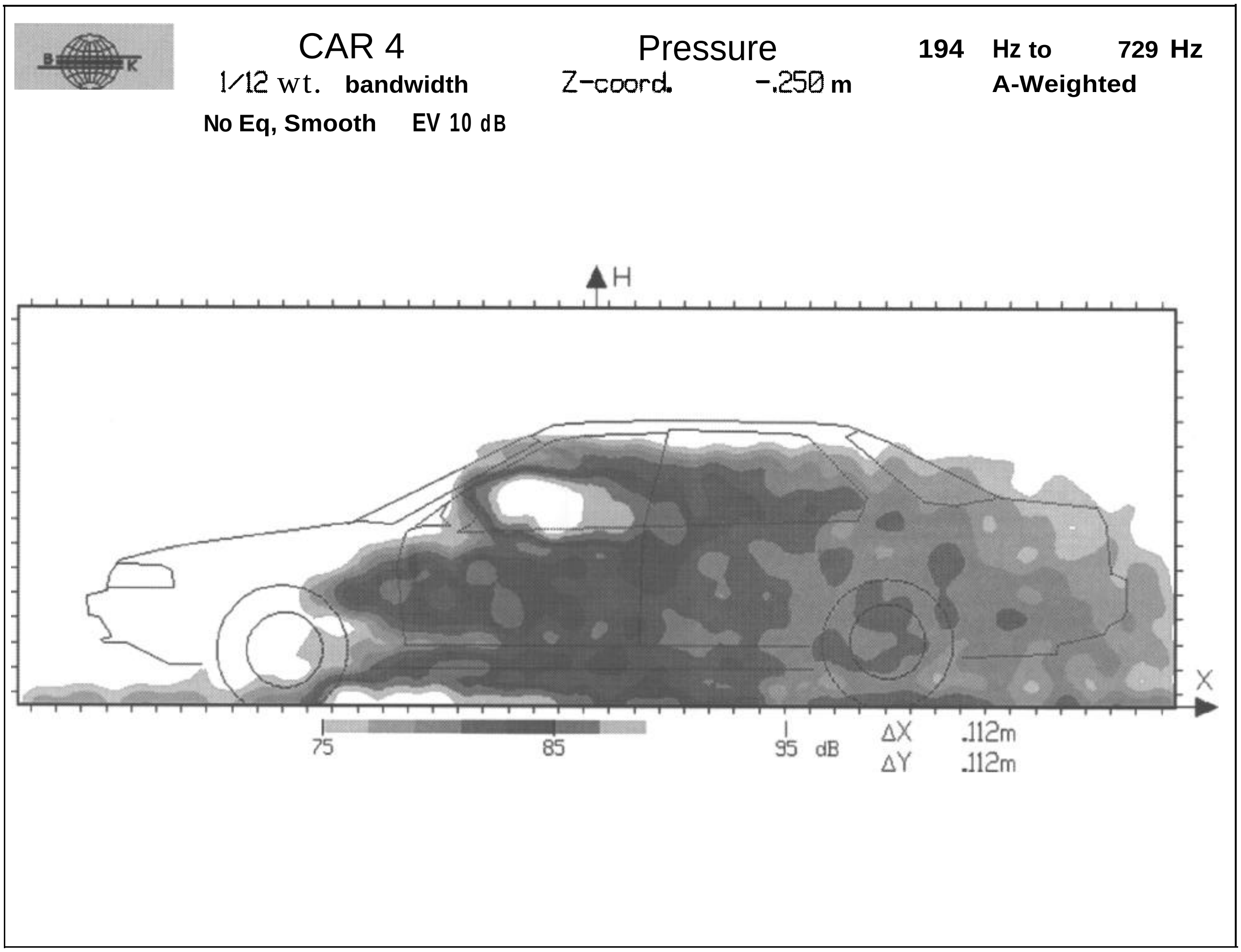

Fig. 12 Outside Sound Pressure Distribution on the Side Surface of a Car measured with 100 km/hour Wind Speed

6. Conclusion

The application of STSF for localization of aerodynamic noise sources has been described and tested. The main conclusions are:

1) If the reference signals have high coherence with the noise sources of interest and low coherence with the self induced wind noise, then the noise sources can be identified in a wind flow.

2) Holography can do a precise noise source localization from measurements taken at a certain distance on the surface of the source.

3) Experiments indicate that it is possible to locate the aerodynamic noise sources on a car body.

7. References

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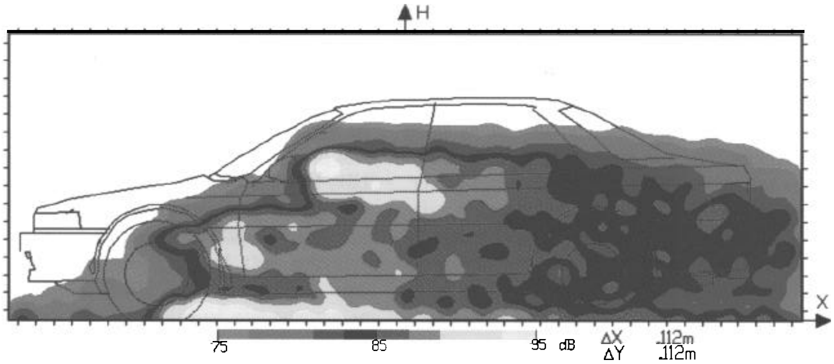
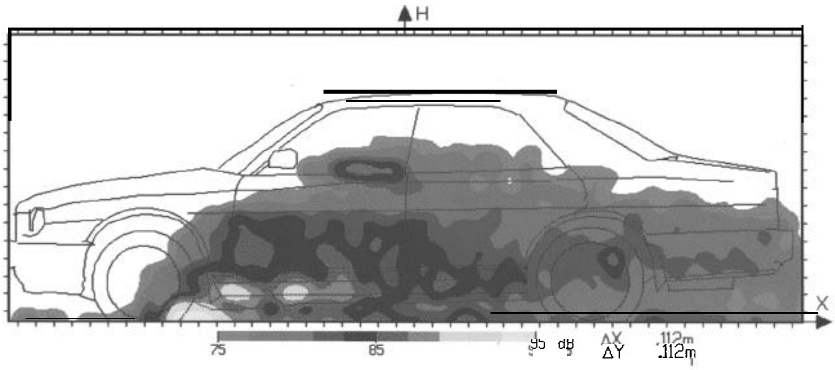




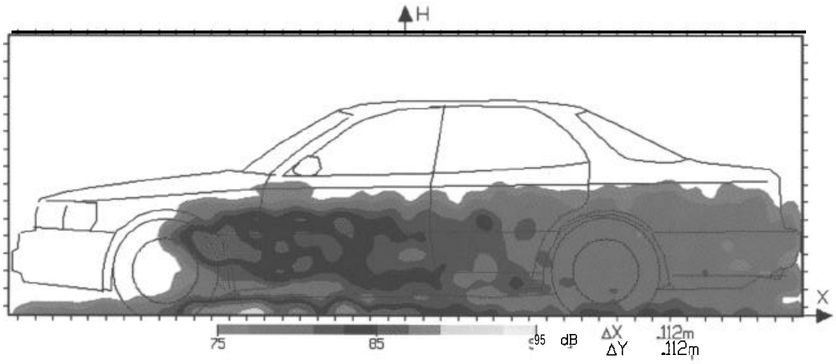
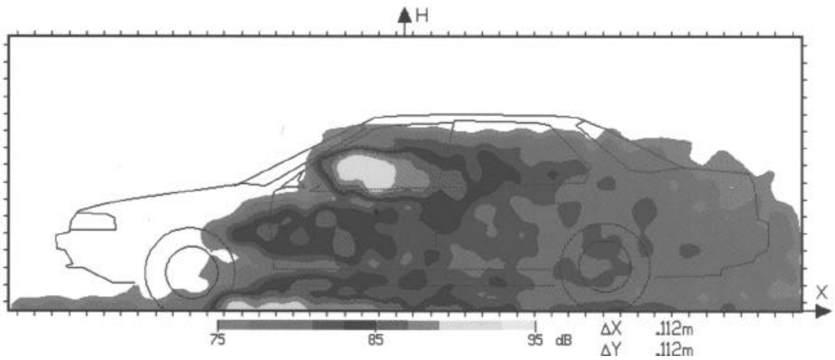


Fig. 13 Outside sound pressure distribution on the side surfaces of four different cars.

Wind speed: 100 km/hour

Frequency range:
194 Hz to 729 Hz A-weighted



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