Aerodynamic noise source identification in wind tunnels using acoustical array techniques

Bernard Ginn, Brüel & Kjær A/S, Nærum, Denmark
Jørgen Hald, Brüel & Kjær A/S, Nærum, Denmark

Abstract
Aerodynamic noise is particularly important for passenger car driving comfort and high speed train community comfort. This paper describes the application of acoustic array systems in wind tunnels to minimise this noise exposure. To investigate car interior aerodynamic noise, measurements are performed on full-size vehicles at different stages during development. Exterior aerodynamic noise is measured at a very early stage, with a solid "clay model". Both car exterior and interior array measurements are presented. To investigate exterior aerodynamic noise produced by high speed trains, wind-tunnel measurements are typically performed on scale models, or on components. Various array systems are described with typical results.

Introduction
Two areas where aerodynamic noise has high attention are passenger car driving comfort and high speed train community comfort. This paper describes the application of acoustical array systems in the endeavour to minimise this noise exposure. At cruising and higher speeds, the aerodynamic noise is the dominant noise source in a car. In relation to car interior, aerodynamic noise, measurements are performed on full-size vehicles in wind tunnels at different stages during the development. Exterior noise can be measured at a very early stage, starting with a solid "clay model", while interior measurements require of course a complete vehicle. Both car exterior and interior array systems and measurements are presented. A research project is outlined where the aim was to find the correlation between the exterior and interior noise changes resulting from design modifications. Knowledge of such correlation will support more effective interior noise reduction measures through design modifications at the clay model stage.
To investigate exterior aerodynamic noise produced by high speed trains, wind tunnel measurements are typically performed on scale models of train sections, or on components such as pantographs. A number of array systems are described to perform this kind of measurements together with some typical results.

Acoustical array measurement methods used in wind tunnels
Exterior methods
The two main methods for measurements on the exterior of vehicles in wind tunnels are near-field holography and beamforming. Other methods are also being used such as acoustical mirrors and surface pressure mapping.
For near-field holography a scanning method can be used where an array of measurement microphones has to be placed close to the vehicle under test and that is usually in the airflow region. A sufficient number of reference microphones is distributed near the vehicle in order to model the independent sound fields in the frequency range of interest. Cross spectra are measured between all the reference microphones and between each reference microphone and each scan microphone. This means that the sound field coherent between the reference microphones and the scan microphones is measured,

whereas the self-induced noise in the microphones, manifest in the autospectra, is suppressed. The microphones must be equipped with windscreens and be positioned to face upwind (fig.1) and any support they may have must be aerodynamically chamfered to minimised unwanted turbulence. If a full microphone array were used no reference microphones would be necessary. However placing such a large structure in the airflow would inevitably produce turbulence. Fortunately, such measurements are usually made with constant wind-tunnel flow speed, therefore a robot-controlled, scanning method with a reduced number of microphones can be employed (fig.1). Judiciously positioned reference microphones can be used to reduce the effect of wind noise. For example, a reference microphone inside a motorcyclist's helmet can be used to map the sound field coherent with this reference (fig.2). Other typical references are the pressure signals measured with a HATS (Head And Torso Simulator) placed inside the vehicle, or a microphone concealed behind the side mirror in order to be shielded from the turbulence.

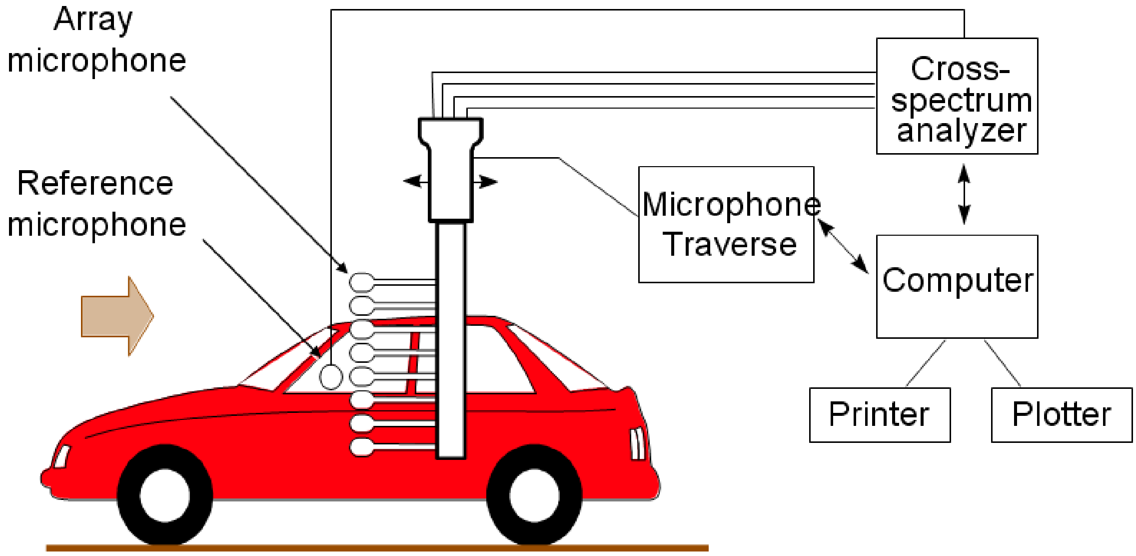


Fig.1. Schematic view of system used for near-field holography measurements in windtunnels using a scanning technique

Fig.2. Near-field holography measurement performed using a robot controlled scan of an array of 8 microphones. A reference microphone is positioned at the motorcyclist's ear to map the sound field coherent with this reference

For beamforming measurements, it is usual to place a half wheel on the floor of the tunnel in order to take advantage of the mirror ground condition. As the array is usually a few metres from the vehicle under test, it is also well outside the airflow region so wind induced noise is reduced. All the cross-spectra are measured simultaneously which enables the wind noise induced in the microphones to be eliminated by using only the cross terms in the complete cross spectrum matrix. The autospectra on the diagonal of this matrix are not used in the further calculation. No references are necessary.
Fig.3, shows a vehicle in a wind tunnel, where the sound distribution was investigated as a function of yaw angle. The vehicle was fully taped to reduce the effects of leakage around seals and to reduce turbulence produced by wheel arches, undercarriage etc.
Using a reference signal from, for example, a microphone positioned behind the side-mirroir, effectively produces a selective beamformer; the noise from around the mirror and A-pillar will be accentuated, whereas the noise contribution from the turbulence produced by the front of the vehicle will be suppressed.

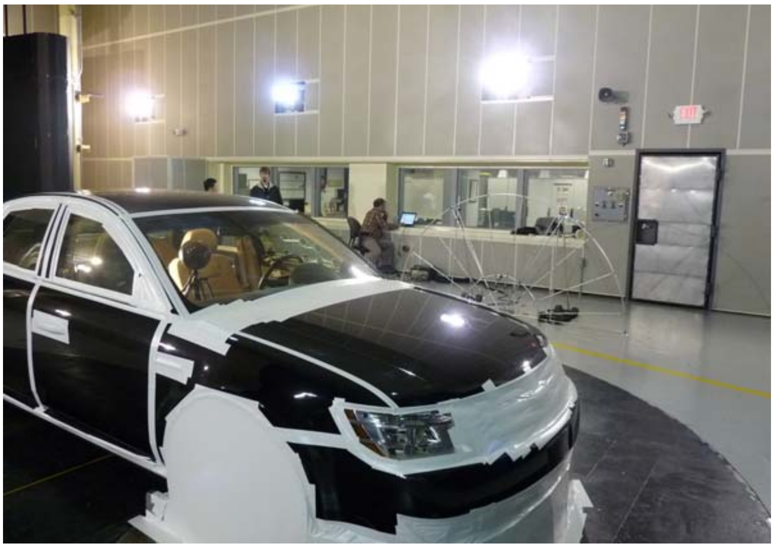


Fig.3. FORD wind tunnel with taped vehicle on rotating plate used to adjust yaw angle. Spherical Beamformer in the cabin, surface microphones on left side window and half wheel beamforming array at 3.8m distance (0 degree yaw)

Interior methods

The results from the exterior measurements are frequently used in conjunction with those made inside the vehicle. A well-proven tool here is a spherical beamformer which is usually placed at head-height at an occupant’s position. The spherical beamformer provides a directional map of acoustical quantities superimposed on a photograph made by stitching together the views seen from the cameras built into the sphere. Not only can quantities such as sound pressure and sound intensity be calculated but also sound quality metrics such as Loudness, Sharpness, Impulsiveness, Articulation Index etc.
For precise noise source localisation within the vehicle cabin, the spherical beamformer is usually used in conjunction with a conformal mapping technique whereby the sound pressure or other acoustical quantity is mapping on a 3-D CAD model of the vehicle interior. Fig.4 shows the results of a conformal mapping made using a spherical beamforming in the driver’s seat. The location of the problematic air vent is clearly seen.

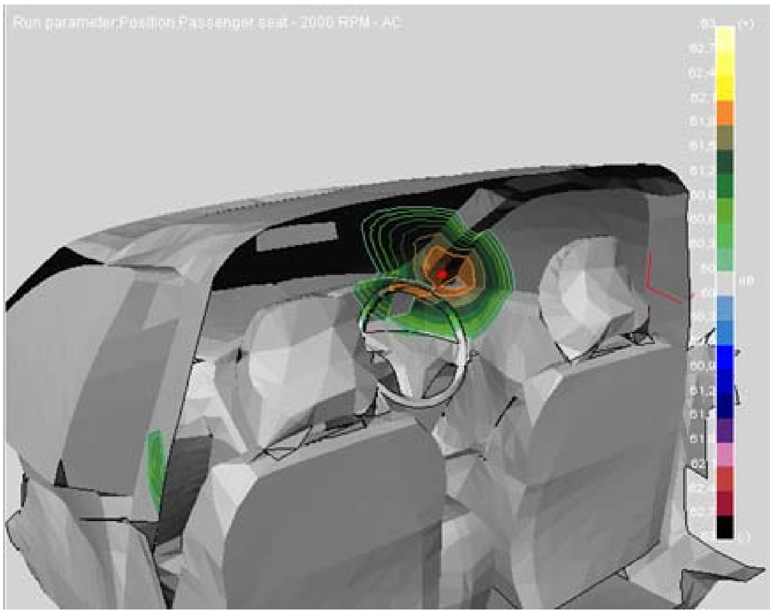


Fig.4. Conformal mapping obtained from measurements made with a spherical beamformer

Another way of producing a conformal acoustical map is to use a hand-held array consisting of a double layer array of microphones in a rectangular grid of typically 8 x 8. The dimensions of the hand-held array depend upon the frequency range of interest. A grid spacing of 3cm x 3cm gives an overall array size of 21cm x 21cm and a frequency range of up to 5kHz. Where access to the surface under investigation is restricted, smaller grids can be used. The double layer array enables the direction of the incident sound energy to be determined which means that reliable measurements are possible even in the reverberant interior of a car.

Vehicle aerodynamic noise

The main sources of aerodynamic noise perceived by the driver are usually the A-pillar and the side mirror. Therefore, exterior beamforming focuses on these areas. Figs.5 and 6 show results using a full wheel, beamforming array hung above the roof of the vehicle and a half wheel array positioned facing the side of the vehicle respectively.

The results were calculated for two different beamforming algorithms. Delay and Sum is the most commonly used beamforming algorithm. Whereas the Non Negative Least Squares algorithm is a deconvolution method well known in the aerospace industry. Another deconvolution method also supported by the present implementation is the DAMAS2 algorithm.

Fig.5 shows how the spatial resolution of a Delay and Sum beamforming sound mapping is improved when NNLS is employed. In Fig.6 sound maps are shown for noise in 16Hz bandwidths. Virtually no difference is noticed for the Delay and Sum results whereas the NNLS shows considerable frequency related detail. In Fig.7 as the yaw angle of the vehicle is increased from 0 to 10 to 20 degrees, one can see that on the leeward side, the amount of turbulent noise produced gradually increases.

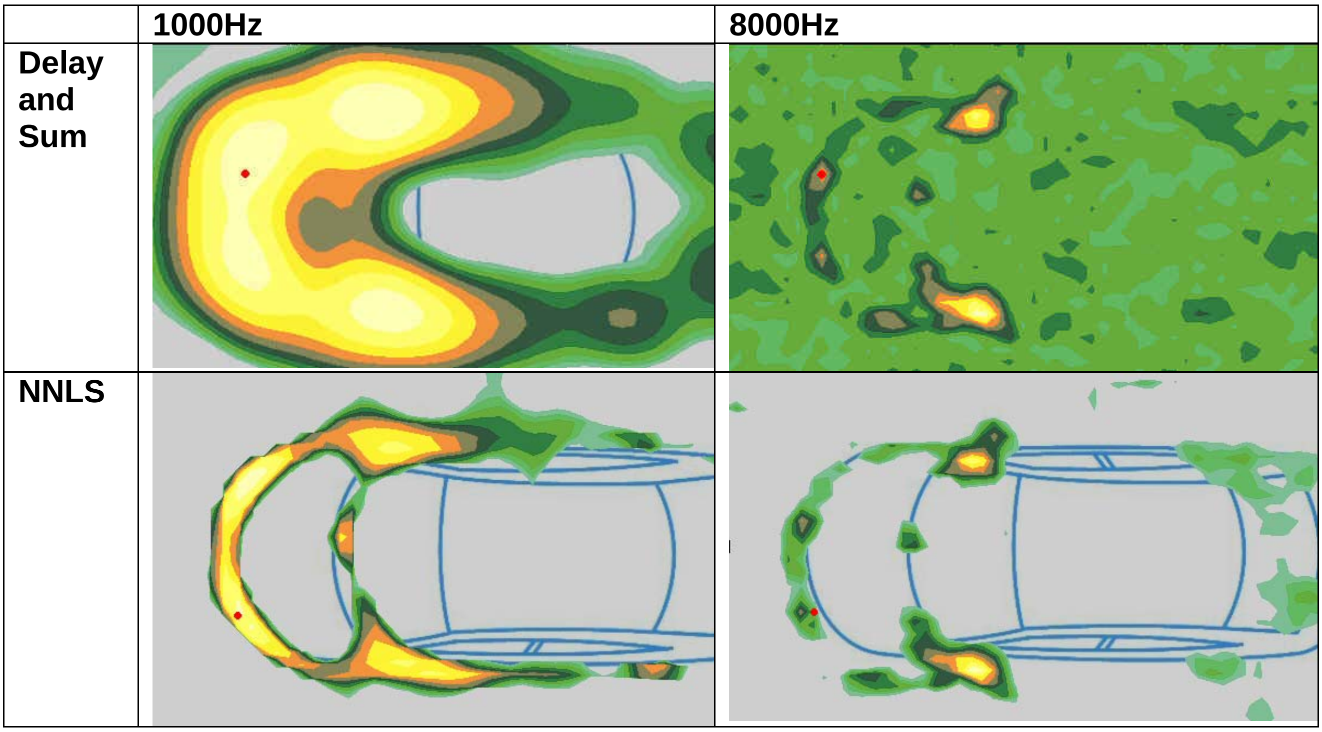


Fig.5. Wheel array supported above test vehicle in windtunnel.
Top row: delay and sum results; bottom row: NNLS (Non-Negative Least Squares) results.
Display range 15dB.

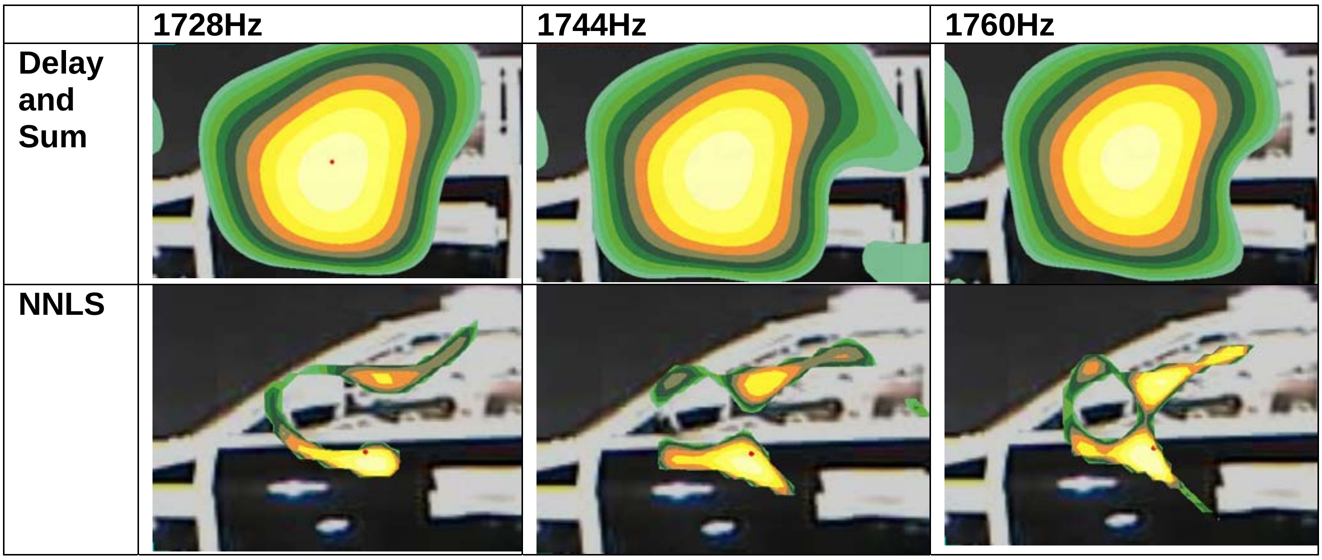


Fig.6. Low intrusion A-pillar and side mirror at -10 degrees yaw. Delay and sum (DAS): top row; Non Negative Least Squares (NNLS) : lower row. All results are calculated onto a vertical plane touching the lower edge of the window. 10dB display range.

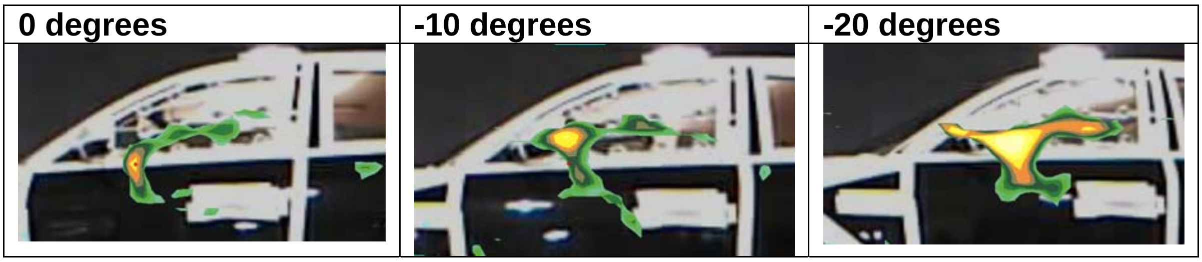


Fig.7. Non Negative Least Squares (NNLS) results for various angles of yaw, frequency range1784 to 1848Hz. Front of vehicle progressively turned towards the half-wheel array. 10dB display range.

A crucial question for vehicle designers is whether the interior noise source ranking for particular A-pillar /side mirror configurations, can be deduced from measurements made at a very early stage in the development process when only a clay model of the proposed design is available for wind tunnel testing. To test this hypothesis, the source distribution over the side door window area was measured externally using planar beamforming and internally using spherical beamforming. The results shown in Fig. 8 are encouraging, in that the same source generating areas are located by means of the external half wheel array and by the internal spherical array and comparable relative changes in source strength are observed from inside and outside. Furthermore, the assumption that the A-pillar /side mirror design which produces the lowest exterior noise, will produce the lowest interior noise is supported.
To measure transfer functions from the indentified sources to the HATS on the driver's seat, a volume velocity source was then used. These transfer functions from an existing vehicle could then conceivably be used when pressure contributions at the driver's ear are required for a new but similar design for which only a clay model exists.

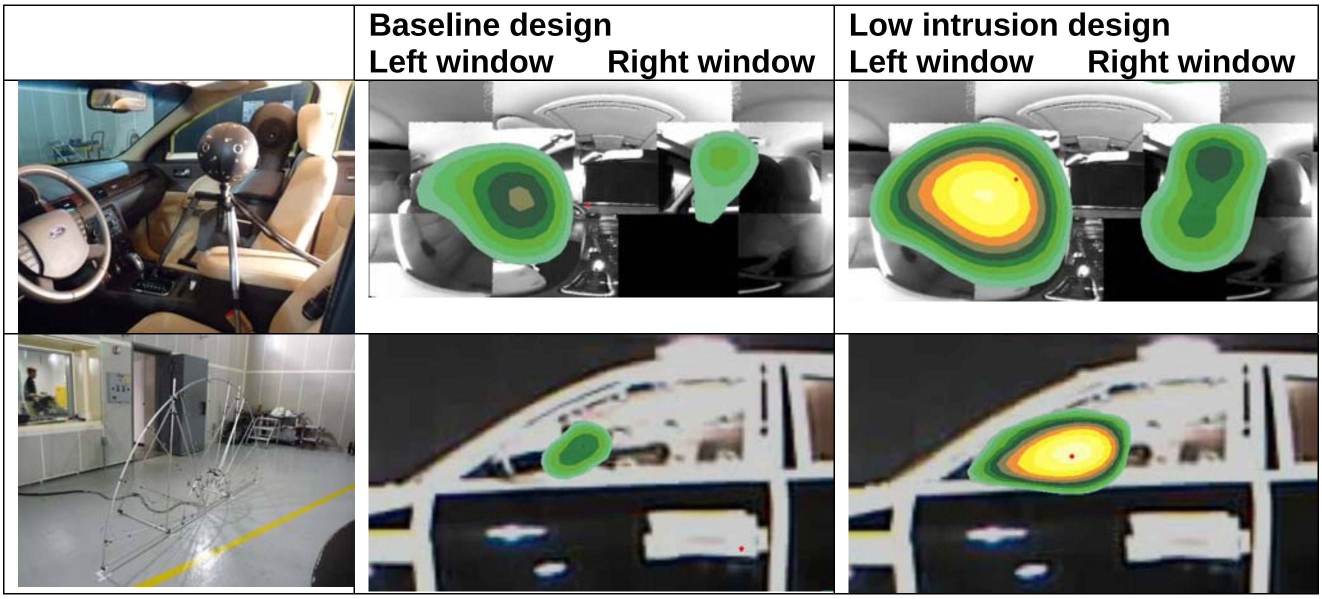


Fig.8. Comparison of beamforming results seen from inside and outside vehicle using spherical beamformer and halfwheel planar beamformer respectively. Yaw angle -10 degrees, 80mph, 800Hz. 10dB display range. The omnidirectional photo from inside the cabin has been folded out flat to show the sources on the left and right side windows

High speed train aerodynamic noise

The noise regulations for high speed trains are intended to protect residents living near railway lines. In 1975, the Japanese Environment Agency demanded that Japanese national Railways should not exceed 75dB(A) maximum noise at a distance of 25metres from the track of the Japanese high speed train known as the Shinkansen. This legislation meant that new Shinkansen trains must reduce noise compared to earlier trainsets. In 2002 the Komaki low-noise wind tunnel was commissioned to develop, low-noise, high-speed Shinkansen trains and to perform advanced research into aerodynamic noise. By using side stream techniques, the tunnel background noise due to the turbulence of the flow has been reduced to 77,9dB(A) at wind speeds of 300 km/hr.

In the wind tunnel test, the frequencies used on the model, are scaled to correspond to the full sized train. In general:

- aerodynamic noise is proportional to the sixth power of the mean velocity above 250km/hr
- observed sound pressure is inversely proportional to the second power of the model scale
- observed sound pressure is inversely proportional to the second power of the distance from the noise source
- There is a simple relationship between the frequency response of the model and that of the full-size train

The smaller the model, the higher must be the frequency response of the measurement system. In the wind tunnel test, a 1:20 scale model of the complete train was used. This means that with an upper limiting frequency of the noise source location system of 20kHz, the model’s predicted highest frequency becomes 1000Hz.

For the beamforming measurements, a random array optimised up to 20kHz, was used, with the microphones flush mounted in a large reflective wall (fig.9).

JRC has also developed the use of an elliptical mirror as a simple method for making high-frequency contour maps. The system had a diameter of 1.4m with a focal length of 2m. A Brüel & Kjær Type 4944, quarter inch ultrasonic microphone is placed at the focal point. A resolution test showed that the measurable frequency range was from 500Hz to 50kHz. The device is connected to a traversing system to scan the object under test.

A quicker way of making these measurements would be to use a random array of Type 4944 microphones and optimise the frequency response up to 50kHz. Examples of the sources which have been investigated in the wind tunnel are the form of the leading head of the Shinkansen, the pantograph, cable heads and wipers and their associated insulators.

Finally, when the components are ready for validation on a full sized train under normal operating conditions, a moving source, beamforming technique can be employed, whereby a wheel (fig.11) or a pentangular array (fig.12) is situated at a safe distance e.g. 4m, from the track and the noise measured as the train passes by.

courtesy of JR Central

Fig.9. Scale model 1:20 of high speed train in wind tunnel. Optimised random array for use up to 20kHz; microphones flush mounted in reflective wall

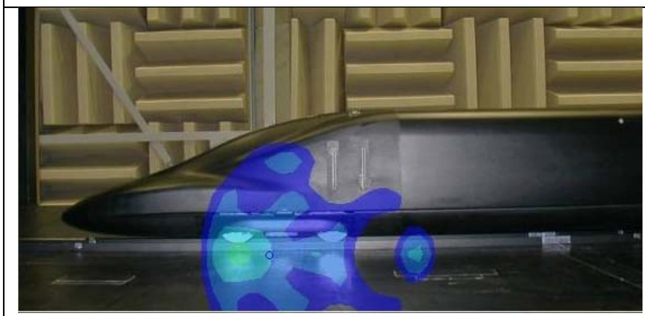
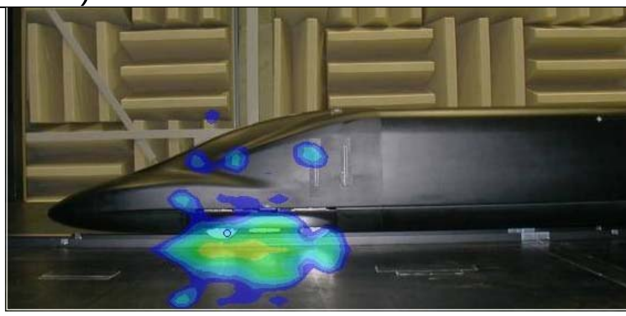
8000Hz (corresponding to 400Hz full scale)	16000Hz (corresponding to 800Hz full scale)
 courtesy of JR Central	 courtesy of JR Central

Fig.10. Contour pressure maps on leading head of 1:20 model of a high speed train

Fig.11. Testing of components on full-sized trains under normal operating conditions: On left, wheel array measuring on high speed train. On right, pentangular array measuring on commuter train

Summary
An overview of acoustic array techniques used in wind tunnels has been presented together with a number of practical results. It has been demonstrated that using correct array designs, a vast amount of information in the frequency and the spatial domain can be obtained. Furthermore, deconvolution algorithms well known in the aerospace industry, have been used to enhance the spatial resolution on acoustic maps obtained using planar beamforming by a factor of approximately three.
There is a correlation between the exterior and interior aerodynamic noise of a vehicle. External beamforming yields the aerodynamic noise source distribution on, for example, the side window. By combining the source distribution with the acoustic transfer functions from the side window to the driver's ear, measured on an existing similar vehicle, it is conceivable to estimate the interior noise from external beamforming measurements made on a clay model or styling buck that has no representation of the interior of the vehicle.
In the endeavour to reduce the aerodynamic noise from high speed trains, array acoustic techniques have proved to be useful tools, with applications in scale model and full scale testing.

Acknowledgements
FORD Motor Company, Dr.Qian Ping and Bill Gulker
Special thanks to Dr.Koji Watanabe, Japan Rail Central.

References

1. Technical Review, Brüel & Kjær publication: “Use of Volume Velocity Sound Source in FRF Measurements” Nr.1 2009
2. Technical Review, Brüel & Kjær publication: “Spatial Transformation of Sound Fields in the Automotive Industry” Nr.1 1995
3. Technical Review, Brüel & Kjær publication: “Beamforming”, Nr.1, 2004
4. Koji Watanabe, “Introduction to Komaki wind tunnel and test results of aerodynamic noise of high speed train models”, Internoise 2003
5. Klaus Ehrenfried, Lars Koop, “Comparison of iterative deconvolution algorithms for the mapping of acoustic sources”, American Institute of Aeronautics and Astronautics, AIAA paper, 2006-2711, 2006