inter.noise 2000
The 29th International Congress and Exhibition on Noise Control Engineering
27-30 August 2000, Nice, FRANCE

I-INCE Classification: 7.2

MICROPHONE ARRAY TECHNOLOGY FOR AIRCRAFT NOISE MEASUREMENTS

M.M. Boone*, T.C.V.D. Dool, P. Sijtsma***, U. Stelwagen****

* TU Delft, P.O. Box 5046, 2600 GA, Delft, Netherlands

** TNO Institute of Applied Physics, P.O. Box 155, 2600 AD, Delft, Netherlands

*** National Aerospace Laboratory NLR, P.O. Box 153, 8300 AD, Emmeloord, Netherlands

Tel.: +31 15 2781471 / Fax: +31 15 2625403 / Email: rinus@akst.tn.tudelft.nl

Keywords:
ARRAYS, AIRCRAFT NOISE, MEASUREMENTS, BEAM STEERING

ABSTRACT
Presently available aircraft noise measurement systems are based on single channel omni-directional microphone technology. An important disadvantage of this approach is that these systems are equally sensitive to other noise sources as to the airplanes to be measured. Furthermore they are sensitive to turbulence noise caused by wind. In this paper new approaches for the measurement of aircraft noise are presented that are based on microphone array technology. Using array technology, extraneous noise sources and wind noise can effectively be suppressed. Results on optimization of array designs and signal processing for this application will be presented that are based on array processing theory and were confirmed by realistic simulations.

1 - INTRODUCTION

Recent developments in our country on the legislation of aircraft noise will probably lead to a new integrated noise measurement and calculation method. These developments coincide with those for new European guidelines for quantifying noise immission, that will also have to be taken into account. Consequently, measurement methods are desired which are based on the A-weighted integrated immission levels, usually called SEL or L_{AX}.

In this paper a new method is described to carry out the required high quality measurements of aircraft noise with microphone array technology. The commonly used measurement methods for aircraft noise are based on single omni-directional microphone transducers. Such systems often suffer from a lack of signal to noise ratio. This means that under many conditions no accurate measurements can be carried out. Commonly known disturbing noise sources are wind noise, traffic noise and local environmental noise. Part of these problems can be circumvented by placing the measurement microphone at a well chosen position. This may help to suppress local noise, but it often means that the microphone has to be placed at a higher position which leads to more wind disturbance. The analysis software of aircraft noise monitoring systems usually validates the measurements by analyzing the immission levels as a function of time and frequency. In that way a decision is made whether the registration is aircraft or other noise; it does not improve the signal to noise ratio. Hence, the best way to obtain measurements with a higher quality is to make a directional measurement that helps to suppress the unwanted noise.

In the next sections we will first give an overview of array technology that is presently used in acoustics and may hence be useful for the problem at hand. Next we will discuss how these techniques can be optimized for the problem of measuring aircraft noise immission. These ideas have been tested in a realistic simulation procedure and based on these results we are presently (at the moment of writing this proceedings paper) in preparation for carrying out test measurements.

2 - OVERVIEW OF ARRAY TECHNOLOGY

Array technology is used in many disciplines, such as seismics, sonar, radar, broadcasting, radio astronomy and also in acoustics. Usually such array measurement procedures are used to obtain directional information from wave fields.

The basic method to obtain directivity is by focusing or beam steering. The term focusing is used when the wave field is curved, beam steering is a special case where the wave front is essentially plane as is usually the case under far field conditions.
The method can directly be compared with an optical lens system, where the lens supplies the necessary delays to the different ray paths such that all energy concentrates in a focal point.
In the case of plane waves the delay and sum procedure can also be understood as a spatial Fourier transform of the wave field. It is a two-dimensional process where first the signals are transformed to the temporal frequency domain and next for each frequency component a second transform takes place to the spatial frequency domain.
It was realized by one of the authors that the beam steering process can also be applied to the spatial cross correlation function of the wave field. In the case of uncorrelated noise sources this can lead to a sparse array system which uses much less microphones than a full linear array but does not suffer from the high side lobe levels that are found when direct beam steering is carried out on sparse array systems. This has led to an array system for directional noise source measurements, known as SYNTACAN [1].
The direct beam steering and spatial correlation beam steering have in common that they are robust to disturbances. This is not the case with so-called high resolution direction finders which rely on the precise knowledge of the wave propagation [2].
In its simplest form, array technology is carried out in only one spatial dimension. However, in many cases resolution is desired in two dimensions, for instance azimuth and elevation, or horizontal and vertical directions. Besides that it must be realized that the array transducers, in our case the microphones, are often omni-directional, meaning that no distinction can be made between the wave field at the front and at the backside of the array. To obtain directivity in all three dimensions, the array configuration must also be three-dimensional, or when no sources are found at the backside, at least two-dimensional. All these rules apply for the case where array technology is used to distinguish between different sources or sub sources and where a high resolution is needed. The procedures may become more complicated when the noise sources are moving. This problem can be tackled by two methods: i) Make the observation time so short that the source direction keeps constant during the measurement time; ii) Apply corrections during the measurement with a so-called swept focus technique.
Based on the afore mentioned principles of spatial cross correlation, time windowing and swept focusing, several array systems have been developed. Descriptions can be found in the literature. The combination of our experience with the one dimensional SYNTACAN [1], the two-dimensional T-shaped cross array [3, 4] and the sparse planar microphone array for wind tunnel measurements [5] have lead to a cooperation to develop a special microphone array for aircraft noise measurements.

3 - ADAPTATION TO AIRCRAFT NOISE MEASUREMENTS

During our research project we investigated different kinds of array geometries and signal processing procedures. Array geometries ranged from simple one-dimensional line arrays to complicated three-dimensional structures. From this study it was concluded that a vertical sparse line array with optimized cross correlation beam steering has a number of important benefits:

- It has a broad main lobe for high elevations of the aircraft passing (end fire behavior) in combination with a high directivity index. Focusing on the moving source is facilitated by the broad main lobe and wind noise and terrestrial noise sources are effectively suppressed.
- It has a narrow main lobe at low elevations (broadside behavior), such that interfering terrestrial noise sources can also effectively be suppressed. Notice that due to the axis-symmetrical beam pattern the focusing is also not critical under these circumstances for the moving airplane.
- Only a small number of microphones are needed and these microphones can be placed in a simply supported vertical mast structure. Environmental protection, especially against moisture and wind can be carried out relatively easily.
- Optimization of the sparsing scheme in combination with cross correlation beam steering processing guarantees low side lobes.

To further optimize the array the relevant frequency range needs to be known.
Therefore the immission spectra of a number of representative airplanes were studied. Measured and calculated emission spectra were obtained for a Fokker 50 in start configuration, a Fokker 100 in cut back (just after the start) and in approach configuration, and an Airbus 340 in approach configuration. These spectra were used to calculate the immission spectra at distances of 250 and 1500 m, taking

into account the geometrical spreading and the atmospheric absorption. Atmospheric absorption gives much attenuation at high frequencies. From these immission spectra the relevant frequency range was estimated by calculation of the A-weighted levels and finding where a low- and high frequency cut-on and cut-off can be taken without noticeable deviation from the true wideband value.
As an example the A-weighted immission spectra of the Fokker 100 in approach configuration are given in figure 1 at distances of 250 and 1500 m.

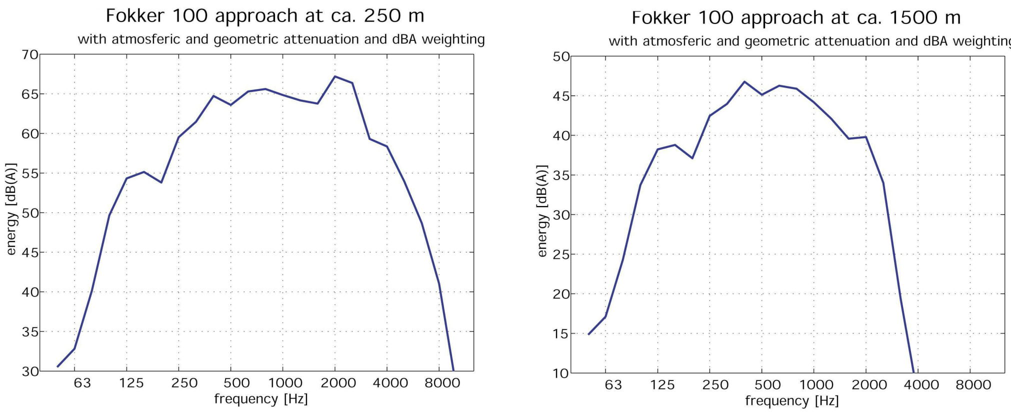


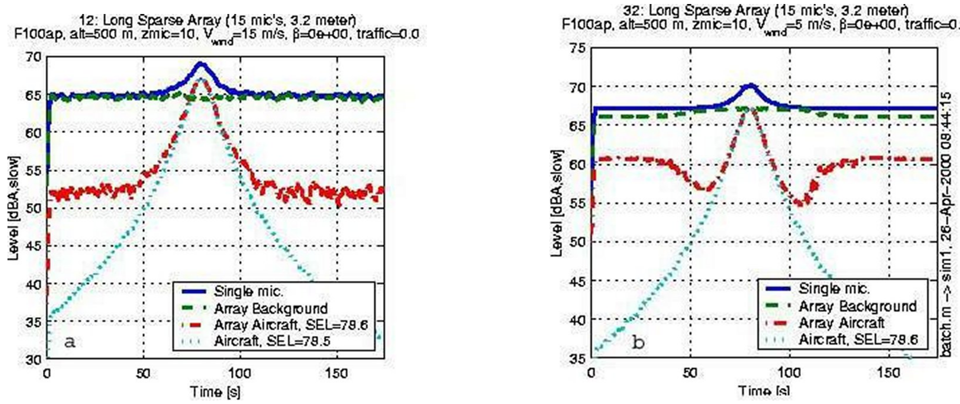
Figure 1: A-weighted immission spectra of Fokker 100 in approach conf. at a distance of 250 and 1500 m.

It was found that in all practical cases a frequency range spanning the octave bands of $125 - 2000$ Hz is sufficient. Based on these findings a 15-elements sparse array was designed with a minimum microphone spacing of 5 cm and a total length of 3.15 m as shown in figure 2.

Figure 2: Lay-out of the specially designed array. It is placed vertically with the dense microphone side up.

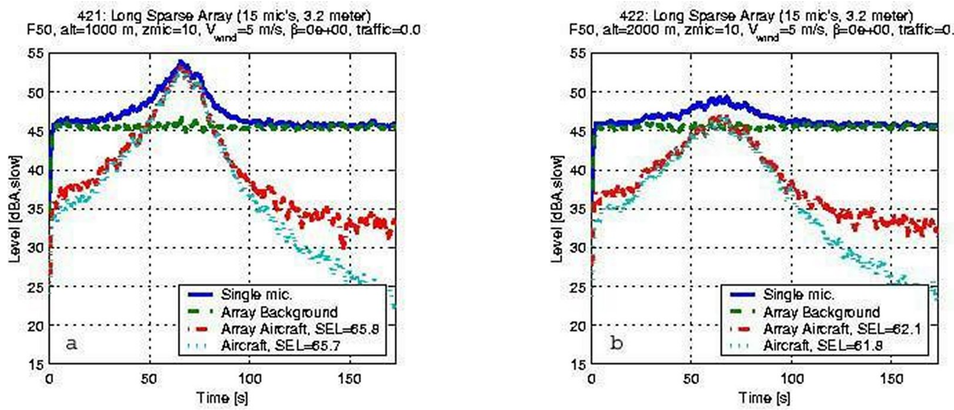
4 - SIMULATION RESULTS

Simulations were carried out as follows. For each type of airplane a representative source signal was generated as a sampled time function. The propagation of these signals through the atmosphere was calculated based on an analytic model of sound propagation from moving sound sources. In this way all dynamic effects of the moving sources such as changing of the wave front as a function of time and Doppler shifts were taken into account. The immission signals were divided into small segments and the appropriate atmospheric absorption was included.
The signals that resulted from this procedure were used in the array analysis software. Notice that with this procedure the simulation tests can easily be replaced with true measurements, sampled directly from real microphones.
The analysis was carried out with the cross correlation beam steering method as standard used with SYNTACAN. From the spatial responses the main lobe was detected and the immission of the airplane was obtained by integration over the main lobe. Next, the immission spectra were A-weighted and integrated as a function of frequency. The resulting short time A-weighted immission levels $L_A(t)$ were averaged with a standard SLOW time averaging.
A typical result is shown in figure 3. Figure 3a shows the situation where a Fokker 100 approaches at a height of 500 m with uncorrelated noise at each microphone caused by a wind speed of 15 m/s. The array gives an improvement of the signal to noise ratio of about 13 dB as compared with a single microphone. Figure 3b shows the same airplane approach, but now with interfering traffic noise, simulated as a line source at ground level at a distance of 100 m. The reference point of the array (the top side) was at a height of 10 m. In this simulation it is clearly seen that when the airplane is at larger distances, where its elevation is small, the traffic noise takes over as the louder source.
As a second example, figure 4 shows simulation results of a Fokker 50 propeller airplane at distances of 1000 m and 2000 m. It clearly shows that also for smaller propeller airplanes the array performs quite well.



(a): With uncorrelated wind noise. **(b):** With traffic noise.

Figure 3: Time records of simulated immission levels showing the array performance in relation to a single microphone.



(a): Fokker 50 at 1000 m. **(b):** Fokker 50 at 2000 m.

Figure 4: Time records of simulated immission levels showing the array performance in relation to a single microphone.

In practice the propagation of sound through the atmosphere is influenced by random disturbances, due to temperature and wind. This leads to so called transverse coherence loss [6]. Its effect has been simulated by a frequency dependent spatial tapering of the spatial cross correlation function of the wave field measured (in simulation) at the array.

Figure 5 shows a comparison of results that are obtained without and with transverse coherence loss for an Airbus 340 approaching at a height of 1000 m. The effective signal to noise ratio is reduced by a few dB's.

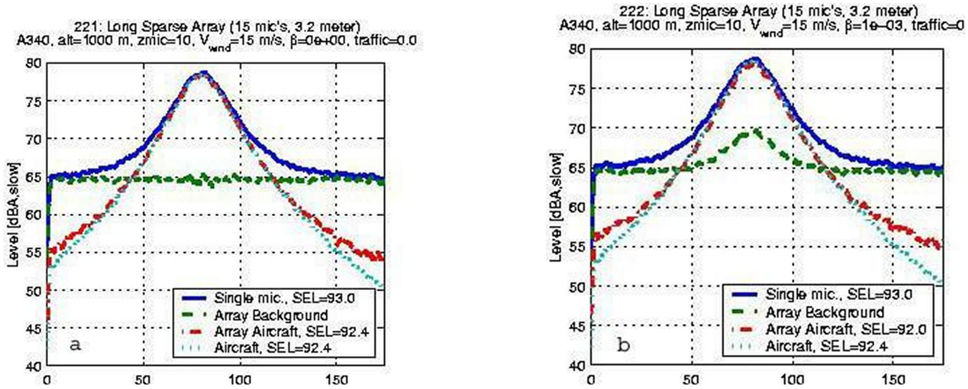
The legends of figures 3, 4 and 5 also show a comparison between the SEL-values of the undisturbed airplane immission and of the array measurements. There are also minor differences.

5 - CONCLUSIONS

From the present research, based on realistic simulations, it has been shown that a vertical sparse array of 3.15 m with only 15 microphones can give an improvement of the signal to noise ratio of about 13 dB for uncorrelated noise interference, such as results from wind on the microphones. It is also shown that a considerable improvement of the signal to noise ratio can be obtained for traffic noise, but the improvement is strongly dependent on the spatial distribution of such directional noise sources in relation to the flight path of the airplane to be measured.

SEL values were calculated for the undisturbed airplane immission and from the array measurements. They show only minor differences, hence proving the suppression of interfering noise while preserving the calibration of the directional immission levels.

Many disturbances, such as those leading to transverse coherence loss, can only be modeled globally. Therefore, the proposed method should be further tested in practice with an experimental array. Such



(a): No coherence loss. **(b):** High coherence loss.

Figure 5: The effect of transverse coherence loss on the array performance.

experiments will also give insight in ways to protect the microphones against the influence of moisture, wind, etc.

ACKNOWLEDGEMENTS
The reported work has been made possible by a project carried out by TU Delft, TNO-TPD and NLR in assignment of the Ministry of Transport, Public Works and Water Management.

REFERENCES

1. **M.M. Boone**, *Design and development of a synthetic acoustic antenna for highly directional sound measurements*, 1987

2. **J. Capon**, High-resolution frequency-wave number spectrum analysis, *Proc. IEEE*, Vol. 57(8), pp. 1408-1418, 1969

3. **M.M. Boone et al.**, Two-dimensional noise source imaging with a T-shaped microphone array, *JASA (submitted in 1999)*

4. **T.C. van den Dool et al.**, Microphone T-array technology for moving noise source measurements, In *Internoise 2000*, 2000

5. **P. Sijtsma**, Optimum arrangements in a planar microphone array, In *First CEAS-ASC Workshop*, 1997

6. **G.A. Daigle et al.**, Line-of-sight propagation through atmospheric turbulence near the ground, *JASA*, Vol. 74(5), pp. 1505-1513, 1983