HISTORY OF ACOUSTIC BEAMFORMING

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ABSTRACT

The development of the beamforming method (also called microphone antenna, phased array of microphones, acoustic telescope, or acoustic camera) is reviewed in this paper. The microphone antenna was invented by Billingsley (1974) and has since seen dramatic improvements due to the availability of better data acquisition and computing hardware. Recent mathematical and software developments invert the beamforming process and allow a quantitative determination of the sources. Beamforming is indispensable for the localization of sound sources on moving objects, on flying aircraft, on high-speed trains, on motor cars in motion, on open rotors like helicopter and wind turbine rotors. In these applications, the ability to follow the motion of the sources is important. The second important applications are source localization tests in the test sections of open and closed wind tunnels. The background noise suppression capability of the beamforming method is required here. The various applications are discussed with a long list of references.

1   INTRODUCTION

Beamforming with arrays of microphones has become a standard method, when the sources of sound have to be investigated in difficult surroundings. Beamforming is indispensable for the localization of sound sources on moving objects, e.g. on flying aircraft, on high-speed trains, or on motor cars in motion. In these applications, the ability to follow the motion of the vehicles is important. The source localization with arrays of microphones is also important in situations, when the sources remain stationary with respect to the microphone array. Here, the advantage of the array is that background noise can be suppressed, which makes it possible to investigate the sources in reverberant or noisy environments, like in wind tunnels or in engine test cells.

The signals from an array of microphones can be used in various ways to investigate the acoustic sources. Beamforming is only one of the available techniques. More general designations of the method are "phased arrays of microphones" and "microphone antenna", which express that the system not only consists of an array of microphones but includes a postprocessing capability. New postprocessing methods can enhance the results substantially in comparison to basic beamforming.

Phased arrays were developed as radar antennas in World War II. Today, they are extensively used in medical imaging with ultrasound. Both applications are active phased arrays, because the waves are not only received but also emitted by the array. Phased arrays of hydrophones were used after WW II for improving SONAR for the localization of submarines. Sound waves were emitted and the echoes evaluated. Passive applications are used by submarines. Large line arrays for low frequencies are towed. The underwater sound application is described by Urick (1983) [1]. Further applications are used in radioastronomy. Most of the current papers on beamforming are on studies for enhancing wanted sound in the environment of unwanted sound and for antennas for mobile communication.

The development of the acoustic beamforming method is described in the following paper. The improvement of the hardware over the years made it possible to increase the number of microphones, the sampling frequency, and the dynamic range of the analysis. The geometry of the microphone distribution was optimized for a large frequency range and low sidelobes. The increase of the computing power enabled the introduction of new data reduction methods.

Beamforming is based on an averaging of sound signals from different receivers. The text book on array signal processing by Johnson & Dudgeon [2] shows the example of a listening device used by the French forces in World War I to detect approaching aircraft. The array consisted of two subarrays with six acoustic sensors in form of inverted horns that were positioned on a hexagon. The sensors of each subarray were fed into one acoustic wave guide. The two ducts of equal length were then routed to the ears of a listening person. The signal arriving at the ear was an average of six sensors comparable to a modern ring array with six microphones. The two subarrays were separated by about two meters, which enhanced the natural directional localization capability of the listening person by a factor of about ten. By changing the two angles of the axis of the listening device, the direction of the incoming sound could be determined. This is an example of real-time beamforming, which has become available only recently with modern computer technology. This first application was on the

sound of aircraft. The noise emission of aircraft remained the driving force for the development of the analysis of microphones arrays up to the present days.

2   THE ACOUSTIC TELESCOPE

It took almost 60 years from the above mentioned WWI episode until the first system based on microphones appeared in 1974 when John Billingsley [3] proposed an acoustic telescope based on an array of microphones. Billingsley and Kinns (1976) [4] presented a hardware system for real-time sound source localization on full-size jet engines. Fourteen ¼" condenser measuring microphones were connected via 100 m long cables to a mini computer, where the signals were digitized with a resolution of 8 bits. The analogue signals could also be stored on a magnetic tape recorder, which set the limit for the number of channels. The sampling frequency was 20 kHz. Analogue low-pass filters satisfied the sampling theorem. Two AD-converters had to share the work load for 14 signals requiring multiplexing. The sampling interval of the ADCs was 6 μs (167 kHz), resulting in a spread of the samples over a duration of 36 μs. This spread between the various signals was not considered in the beamforming software. The computer had a memory of 48 kilobytes. The data and results were stored on floppy disks with a capacity of 0.3 Mbytes. The signals were processed online and the results were displayed colour coded on a colour TV screen. The technical setup of the system was already very similar to modern ones. The three following decades saw increases of sampling frequency, digitization resolution, number of microphones, and improvements of the software.

The paper of Billingsley and Kinns [4] was a first application to a technical problem, the noise emission of the Rolls-Royce/SNECMA Olympus engine (the engine of the Concorde). The paper includes a theoretical analysis of the system performance for a line array with equidistant microphones based on uncorrelated and even for correlated omni-directional sound radiators. Correlated sources were considered appropriate for jet engine data, which were dominated by jet mixing noise in those times. The presence of ground reflections is included in the analysis and the use in a moving airstream is discussed. The consideration of source correlation was first proposed and investigated by Kinns (1976) and tested on a Viper engine [5]. The consideration of source correlation is missing in all modern papers.

3   THE ANALYSIS OF MOVING SOURCES

3.1   Trains

The capability for analyzing the sources on moving objects was extensively used in the investigation of the sources on high-speed trains [7-18]. This was a very challenging application because the measuring distances were in the order of 5 m and the train speeds were as high as 80 m/s, which required very short averaging times in the order of 0.05 s. DLR started in 1977 recording microphone signals with line arrays of microphones. Initially the data were reduced by Toltec Data Ltd., Cambridge, UK. The line array consisted of 15 equidistant microphones and was oriented either horizontally or vertically, enabling source localization in the horizontal and vertical directions, respectively. The 15 microphone signals and the signal of a light barrier for recording the position of the train axles were digitized with

a resolution of 12 bits and recorded on magnetic tape with pulse coded modulation (PCM). The main objectives were narrow-band spectra of the sound emission, which required the implementation of a swept-focus analysis. This led to a de-dopplerization of the signals and an increased averaging time [8,9] for a statistically more stable result. Source motion required resampling of the data for focus positions on the moving object.

Starting 1981, DLR developed its own data reduction programs with a newly acquired mini computer. The implementation of linear interpolation between the samples of the original time series improved the signal-to-noise ratio of the source maps. In order to improve the dynamic range, shading according to Dolph (1946) [19] was always used. This reduced the level of the nearest sidelobes to 26 dB below the main lobe. An important observation of these tests was that the sound radiation of the wheels was dominated by their Eigenfrequencies, which did not change with train speed. The performance of various wheel sound absorbers could be compared with a single train passage.

One problem of the line arrays are the aliases occurring for high frequencies when the wave lengths are less than one half of the microphone separation. To solve this problem, nested arrays were introduced [12]. 29 microphones could be setup such that three subarrays with 15 microphones were created, each subarray with half the microphone separation of the larger array. Nested arrays with 25 Microphones were earlier introduced by IABG of Munich in the German-French Cooperation on railway noise DEUFRAKO (no reference).

Two dimensional source maps could be determined by employing x- arrays [10-18]. When conventional beamforming is used, the maps are dominated by the sidelobe pattern of this array type. A processing method of Élias [42] solves this problem to a large extent. Special spiral arrays and distributed arrays with larger numbers of microphones were developed to improve the two-dimensional mapping capability (see below).

3.2 Aircraft

The next big application was the source localization on flying aircraft. Only measurements on flying aircraft provide reliable results of the engine and airframe noise emissions of a certain aircraft type. The airframe noise emission depends on airspeed, slat and flap setting, landing gear extension, and aircraft mass.

The capability of acoustic imaging on a flying aircraft was first shown by Howell et al (1986) [20]. A line array of four microphones separated by 3.802 m was used on flyovers of a Lockheed Tristar. A longitudinal scan (line array oriented in the flight direction) showed for the blade passing frequency of the wing engines one broad peak during the flyover, because the central tail engine was run at flight idle. A transverse scan identified the locations of the two wing engines. While the track is well defined for trains, this is not the case for flyovers. A de-dopplerization requires an accurate knowledge of the track of the aircraft, and this was obtained by Howell et al with a camera on a tripod. The camera was rotated to follow the aircraft and the elevation and tilt angles were continuously recorded in the form of sine wave frequencies between 4 and 8 kHz. A pulse was also recorded for each picture taken. The data reduction for this tracking procedure is very laborious. The distance was obtained from the known sizes of the aircraft. The rms accuracy of the tracking was 2.16 m (flight direction), 0.15 m (off track) and 0.88 m (altitude) for a flyover altitude of 134 m.

Like in the procedure of DLR (see above) the resampling of the signals was performed with linear interpolation rather than taking the nearest sample of the time series. Howell et al studied the signal-to-noise ratio of these two procedures with a simulation of a band-limited random noise (1200 Hz to 1800 Hz) emitted by a moving source (Ma=0.3, altitude 91,5 m). They concluded that the signal-to-noise levels depend considerably on the sampling rates. Their results are tabulated in table 1. The sampling rates were 5 kHz, 10 kHz, and 50 kHz, the resampling rate 5 kHz in all cases. It can be concluded that the sampling rate of the data acquisition system should be at least four times the maximum frequency of interest for a signal to noise ratio of 35 dB. The paper of Piet et al. [26] comes to a similar conclusion.

Table 1. Improvement of signal-to-noise ratio by increasing the sampling rate for a constant resampling rate of the signals in the moving frame of reference. Results are for band-limited random noise of 1200 Hz to 1800 Hz.

Sampling rate	5 kHz	10 kHz	50 kHz
Resampling rate	5 kHz	5 kHz	5 kHz
Max frequency of analysis	2.5 kHz	2.5 kHz	2.5 kHz
Ratio sampling/max freq.	2	4	10
S/N ratio: nearest available sample	10 dB	18 dB	20 dB
S/N ratio: linear interpolation	20 dB	35 dB	60 dB

A nested line array consisting of 29 microphones was applied by Michel et al (1997) [21] in order to study the noise emission of a Tornado combat aircraft. Flyover altitudes were in the order of 35 m and flight Mach numbers up to Ma=0.8. The line array was oriented in the flight direction in order to separate the sources along the longitudinal axis of the aircraft. The PC-based data acquisition system was able to acquire 32 channels with a sampling rate of 25 kHz and a resolution of 16 bits. The aircraft track was determined with two camera-based systems. Two flights were performed, the first one with external stores and the second one with stores removed. Three different flight Mach numbers were investigated over the measuring position and the engine power was varied in level flight. Low power resulted in a decelerated aircraft, normal power in a flight with constant speed, and high power in an accelerated aircraft. Two surprising results were found. The flight without external stores was noisier than the one with externally mounted missiles and fuel tanks. This was caused by the mounting clamps below the wing and on the fuselage that were exposed to the high-speed airstream and generated extremely high levels of airframe noise. The second surprise was a strong airframe noise source on the inlets of the engines, when the engines were operated in flight idle. The noise of the aircraft remained almost the same in spite of the engines being operated idle. The cause was the separated flow on the engine inlets. Broadband shock noise, a noise caused by the interaction of the jet's turbulence with the periodic mean flow field of an underexpanded supersonic jet could also be identified.

The next flyover test was on a large number of aircraft in the final approach on the airport of Frankfurt (Main), which was reported by Michel et al. (1998) [22].The array consisted of

111 microphones. The positions of 96 microphones (five identical sectors and one microphone in the center) were determined with an evolution strategy, a Monte Carlo method. The cost function was a large sidelobe suppression capability for three frequencies separated by an octave. 15 more microphones were added in the final test. All microphones were mounted on a wooden ground plate of 8 m by 8 m. The flyover altitude was in the range of 35 m to 40 m. The tracking was achieved with three (infrared) laser distance meters, which measured the altitude of the wing and gave a trigger signal when a target was acquired. A surprising result of this investigation was that many aircraft emit tones from their wings, tones that are prominently visible in the dedopplerized spectra and dominate the noise emission in one case. It is now known that the tones are generated by cavities in the underwing surface.

A flyover test on landing aircraft was performed almost at the same time by employing an x-array by Piet et al (1999) [23]. The data reduction of the x-array was substantially improved by the method presented by Élias (1995) [24], which can also be applied in the time domain. Further flyover tests are reported in references [25-30].

3.3   Other applications with moving focus

The external sound emission of automobiles depends to a large extend on the wheel-road noise, which can hardly be tested in the laboratory or in wind tunnels under realistic tire loads. A test with a phased array of microphones on different cars was performed by Barsikow et al. [31-34]. These tests demonstrated that wind noise can be observed on the mirror. The tire-road noise appeared to be higher on the lighter rear axle of the tested front wheel drive cars.

A further application is the tracking and investigation of the wake vortices of aircraft with microphone arrays. [35-38]. Wake vortices of landing aircraft emit a low-level and low-frequency sound, which can be used for the tracking of their positions. The results demonstrated that wake vortices can be detected and characterized by their radiated sound. Very large arrays are required because the emitted frequencies are very low.

Interesting applications are beamforming tests on rotating machinery, like helicopter and wind turbine rotors [39-42]. The focus positions have to follow the motion of the blades in these cases.

4   HARDWARE DEVELOPMENT

The improvement of the beamforming method depended on the development of the hardware. This shall be demonstrated with the hardware development at DLR Berlin.

- The first hardware used was an analogue tape recorder Sangamo Sabre VII with a PCM front end with 12 Bit ADC (1977).
- In a second step this PCM front end was attached to an Atari computer with sufficient memory (Motorola 6800 CPU). This avoided the technical problems with the tape recorder (1981).
- The first PC based system was equipped with four cards RTI860 with four 16 bit ADCs each. More than 16 channels required multiplexing (1989).

- The next PC-based system supported 128 channels with four 16 bit ADC cards for 32 channels each (1995).
- In a next step, 24 bit ADCs (available at low prizes for audio system applications) were used. The ADCs were relocated in separate small boxes close to the microphones to reduce the contamination of the signals by spurious noise. The digital data stream of 32 channels was transmitted over one CAT 5 computer network cable to the PC. This reduced the installation time of large arrays in the field dramatically. Sampling frequency was limited to 50 kHz, which is sufficient for flyover tests. The effective dynamic range was more than 100 dB.
- This system was further developed, by incorporating 24 Bit ADCs with sampling frequencies of up to 196 kHz for 128 channels. This system can also be used for model tests where the frequencies are higher inversely to the model scale factor.

Multi-channel systems with 24 bit ADCs and high sampling rates can be bought on the market in the meantime.

The data reduction for large arrays is very time consuming, especially if each one-third octave band is studied with a different subarray of microphones. While a simple data reduction required times in the order of days 10 years ago, the work on more complex reductions can be performed in fractions of an hour on current day computers.

5   NOISE TESTS IN STATIONARY ENVIRONMENTS

The other big applications of phased arrays of microphones are noise measurements in wind tunnels. Here the problems are high background noise levels, disturbances by the shear layers of free-jet facilities or the boundary layers in closed test sections. In closed test sections the wall reflections have to be accounted for. The convection of the sound waves by the tunnel flow has to be considered in the data reduction. The data reduction for beamforming is discussed in the book of Johnson and Dudgeon. [2]. Special problems and developments of beamforming in acoustic testing are addressed in the chapter "Beamforming in acoustic testing" by Dougherty (2002) [43].

Various improvements of the data reduction procedures are discussed. One important procedure is the removal of flow noise by removing the diagonal elements of the cross-spectral matrix. This can also be done in the time domain [44] and can be performed with almost no burden in the data reduction.

The influence of reflections on the wind-tunnel walls are discussed by Dougherty [43] and specially addressed by Guidati et al. [45,46].

Dougherty [43] also discusses beamforming based in the Eigenvectors of the cross-spectral matrix. This is known as proper orthogonal decomposition (POD) or the very similar singular value decomposition (SVD). This decomposition can improve the beamforming maps substantially in certain cases. An example is presented by Sarradj (2005) [47].

One problem in open jet wind tunnels is the phase distortion introduced when the sound waves pass the free shear layer. The problem was addressed by Koop and Ehrenfried [48]. They use a high-frequency sinusoidal sound source in the source region and introduce a phase correction procedure that keeps the signal sinusoidal in the array microphone signals. They

demonstrated that the signal coherence between the array microphones was significantly increased and the usable frequency range substantially increased by this procedure.

A number of papers discuss various further problems of testing in wind tunnels [49-54].

The microphone positions also have an influence on the results. This problem is discussed in [2] and in various other papers, e.g. [55,56]. Highly irregular positions are only reasonable in prefabricated arrays, like those installed in wind tunnel walls. Arrays to be installed for a flight-test campaign require some regularity to simplify cabling and identification of the microphone belonging to a certain channel. Arrays consisting of spirals or of several circles with an uneven number of regularly spaced microphones seem to be best.

Beamforming can also be applied to open air engine test beds and closed engine test cells. The latter application is dominated by large background noise levels. DLR is currently extending the beamforming method to this application.

The practical aspects of performing acoustic phased array tests in wind tunnels are discussed in detail in the chapter "Aeroacoustic phased array testing in low-speed wind tunnels" by Underbrink (2002) [57]. A large number of papers can be found in the literature [56-80].

6 THE COMBINATION WITH A VIDEO CAMERA

A combination of a microphone antenna with a digital camera was presented by GFaI on the Hannover Messe 1999 (see figure 1) and marketed as "Acoustic Camera". The maps were computed almost in real time and overlaid on the video picture. Thus the sound sources could be "seen" on the noise emitting object. This impressed the media and the public very much and helped the microphone array technique to become known as an interesting acoustic testing method.

The microphones were installed near the edge of a rectangular box in this first model. As a consequence, the sensitivity of the array was likely dominated by a strong frequency dependence of the sensitivity. Newer models have an acoustically transparent design.

The underlying data analysis of Heinz et al. 1999 [83] appears to be conventional beamforming.

Fig. 1. Acoustic Camera: Combination of a microphone array with a video camera.

Microphone antennas with integrated video camera are now commercially available from various sources.

Recently, an array with the microphones arranged on an acoustic transparent spherical surface became available. This model allows a beamforming operation in all directions, especially in enclosures. It can also be used to reconstruct the sound field in the vicinity of the sphere.

7 INVERSE METHODS

The beamforming maps are the result of a convolution of the point sources with the point-spread function [2]. The sound pressure levels of the maps are only reliable for point sources if the source positions have a sufficiently large separation. Sources along a line or distributed over an area or over a source volume yield results that depend on the beam width of the point-spread function. The consequence is that amplitudes of sound sources are very difficult to derive from beamforming maps and require experience. There are some attempts to achieve quantitative results by integrating certain regions of the map.

The source levels of the point sources can only be determined if it is possible to invert the convolution. The result would be a set of point sources. In order to do this the point spread function of the array has to be calculated for every possible source position and for each narrow-band frequency of interest. The source levels of the unknown sources have then to be determined with a least square fit with the condition that only positive source levels are permitted. This deconvolution is in principal possible but yields huge and badly conditioned matrices. Special iterative procedures are required to solve them.

A simpler version is the CLEAN algorithm, which was applied to aeroacoustic sources by Dougherty and Stoker (1998) [84]. Here the point spread function of only the strongest source is calculated and the model maps for small point sources located in the peak position of the map are successively subtracted from the beamforming map, which is cleaned by this procedure from all the sidelobes connected with the main lobe. However, the method works only well in the case of a few well localised sources.

A first procedure proposed to solve the complete inverse problem was published by Brühl and Röder (2000) [85]. Documented procedures were published in recent years [86-90]. Three methods are compared by Ehrenfried and Koop (2006) [91].

The deconvolution of the beamforming maps of moving sources is more difficult, because the sidelobes of the point spread function have a different frequency. Guérin et al. (2006) [92] propose a method to compute an average point spread function for the broadband noise of moving sources with the condition that the narrow-band levels of the sources are constant in neighbouring frequency bands.

Blacodon and Élias propose a different method. They generate a cross-spectral matrix for each possible point source. The amplitudes of the sources are then determined with a least square fit between the modelled and the measured cross-spectral matrix. The beamforming map is only required to estimate the positions of possible sources. [93,94].

8 CONCLUSIONS

The microphone array has become a standard method for localizing the noise sources on aircraft, trains, cars and other machinery. The performance of conventional beamforming depends to a large extend on a good design of the array geometry and on a good beamforming software. The recent developments of inverse methods make it possible for the first time to determine the strengths of the sources. However, the computational effort required for this is very high.

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