Some Research Challenges of *Acoustic Camera*

Miljko M. Erić

Abstract —**Application of array processing principle and techniques in *acoustic camera* is a challenging research problem. Discussions about some of those challenges are given in this paper. Theoretical background of acoustical near-field and far-field beamforming is highlighted in this paper. Generic versions of near-field and far-field delay and sum of beamformers are discussed. Those versions are the basis for further research steps. Some experimental results of near-field beamforming are presented using realized microphone array and multichannel acquisition system.**

Keywords **— acoustic camera, near-field beamforming, spherical beamforming, acoustic holography, microphone array, array processing**

I. Introduction

Acoustic camera appeared on the market as a commercial product more than ten years ago and it is now commercially available from various sources [1,2,3,4,5]. The idea of acoustic camera to do noise/sound source identification and quantification and to perform a picture of acoustic environment by array processing of multidimensional acoustic signals received by microphone array and to overlay that acoustic picture to the video picture. So, it is a device with integrated microphone array and digital video camera, which provides visualization of acoustic environment.

With acoustic camera it is possible to visualize the results of acoustic source characterization so it became an attractive commercial test instrument used not just in research laboratories but in industry, as well. Acoustic camera is just one phase in long history of development of microphone array technology, [6]. Possible applications of acoustic camera as test equipment are nondestructive measurements for noise/sound identification in interior and exterior of vehicles [7], trains and airplanes [8,9], measurements in wind tunnels, etc. Acoustic camera can also be built in complex platforms such as underwater unmanned vehicles [10], robots and robotized platforms etc. It can be also used for passive acoustical sensing in battlefield [11].

Acoustic camera is used both for near-field as well as far-field signal scenario. Two basic well known principles applied in solutions of acoustic cameras are: **Near-Filed Acoustic Holography (**NAH) [12] and **beamforming** [13,14,15,16,17].

Near-field Acoustic Holography (NAH) is based on the use of rectangular planar microphone array placed relatively close to the acoustic source (some wavelengths of the highest frequency in the sound spectrum). Microphones in microphone array are placed on the distance equal to the half of the wavelength of the highest frequency in the spectrum of the signal (Niquist criteria for the spatial domain). So, since limitation in choosing of microphone distances due to their physical dimensions, limits the spectral bandwidth of the signal on the upper limit, NAH is mainly applied for the low frequency range. Spacing of microphones and size of microphone array determines spatial resolution. 2D Fourier transformation is applied for the signals acquired with microphone array. From this spatial spectrum and knowledge of the law of acoustic signal propagation, acoustic pressure of the signal source can be back restored using known Green functions. But that process can be done just for the propagation planes which are parallel to the measurement plane (plane of microphone array). In order to localize a source in 3D, measurement plan (microphone array) has to span the complete object. NAH technique is very efficient with scenario with one point sound source, but the story is more complicated in multisource signal scenario and some complex preprocessing techniques have to be applied in that case. In NAH technique size of tested object has to be smaller than array size. Data acquired from the plane array in NAH can be also used for near-far beamforming.

Beamforming is another technique applied in acoustic camera. Acoustic beamforming has a long history. There are lot of scientific papers and books related to the theoretical as well as practical aspects of acoustic beamforming but there are some specific aspects of its application in acoustic camera. Two basic acoustic beamforming principles are applied in acoustic cameras: far-filed and near-field beamforming.

Far-field beamforming is applied in the first commercial solutions of acoustic camera. Far-field beamforming is beamforming of plane waves, so it is assumed that acoustic source is far from the microphone array. Acoustic beamforming provides Direction Of Arrivals (DOAs) of acoustic signals, so the measurement of source distances are additionally needed in order to identify the sources. In that case line of sight between microphone array and sound sources are required. Since the mathematical model of the plane waves on the microphone array does not depend on sound source locations, far-field beamforming provides estimation of relative sound preasure on the microphone array but not on the locations of the sound sources.

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Near-field beamforming is beamforming of sphere waves so it is the case when the sound sources are on the small distances (some wavelengths) form the microphone array. Mathematical model of the signal on microphone array in near filed scenario depends on the locations of the sound sources, so the near-field beamforming can directly identify locations of acoustic sources and provide acoustic picture in spatial sector of interests (DOAs in far field, became locations in near-filed beamforming). In literature near-field beamforming is also named focalization [18].

Spherical beamforming [19] is a special version of acoustic beamforming applied in acoustic camera. It is based on the use of spherical microphone array. It can be applied in reflective sound environment and it is used for measurement in interior of vehicles, trains and airplanes. Advantage of spherical geometry is that spatial resolution is almost equal in all spatial directions. It is also possible to do some transformation of the signals acquired from non spherical microphone array to provide virtual spherical array and then apply spherical beamforming.

In acoustic beamforming there are no limitations regarding the geometry of microphone array. Microphone array can be of any geometry but all possible microphones geometries with the same number of microphones are not equally good. Ambiguity, spatial resolution and side lobes properties of acoustic beamforming are directly related to the geometry of microphone array. In known solutions of commercial acoustic cameras planar circular and volume spherical geometry are mostly used. Planar '*star*' geometry with non-uniform microphone distances and big microphone size are also used for far-field measurements.

It is known that linear microphone arrays are fully ambiguous so this geometry is not used in acoustic camera. All planar geometries of microphone array have ambiguity of the front/back type. Volume microphone geometry is generally un-ambiguous in volume, but if spacing between microphones is random, then the level of the side-lobes in beamforming can be significant. For ambiguity characterization of the antenna/microphone array an ambiguity function [20] can be used defined as a normalized measure of co-linearity of two steering vectors in array manifold for different DOAs. If values of ambiguity function is equal to one, perfect ambiguity occurs.

Spatial resolution is defined as the shortest distance at which two point sources can be separated. In far-field acoustic beamforming it is equivalent to the smaller difference of DOAs which can be separated. From the theory of array processing it is well known that if the size of antenna/microphone array (aperture) is as big as possible, the resolution properties are better. With the same number of microphones, array aperture can be increased with non-uniform distances between microphones, but in that case, side-lobes in beamforming appear. It is also known that spatial resolution is frequency dependent, so the lower frequency means lower spatial resolution. Due to those properties, near field acoustic holography NAH and beamforming are complementary techniques. The first can be used for low and second for high frequency range of acoustic signals.

Side-lobe levels in beamforming are a very important fact in acoustic camera application since it directly limits dynamic range in acoustic mapping. It is directly influenced by the geometry and aperture of the microphone array. Bigger aperture and the bigger number of microphones in the array means smaller side lobe levels. The level difference between the two sound sources that can be clearly identified and detected is called *plot dynamic* [7]. If the level difference between two real sources is greater than the plot dynamic, louder sources mask quieter sources. Side lobes can be further suppressed by some additional processing but it is still one of the key problems in acoustic beamforming. Known leading producers of acoustic cameras claim that dynamic range of its acoustic cameras is from 25 to 40 dB but it is not quite clear how it is provided, since they reference to the their patented solutions.

Motivation for this research is related to the Serbian national project of Ministry of Science and Technological Development TR 32026 called "*Integration and Harmonization of Sound Insulation in Buildings in the Context of Sustainable Housing*". In this project we tend to apply technical solutions of acoustic camera for development and verification of solution for sound insulation in buildings. To the author's best knowledge acoustic camera is not so far used for this purpose so it seems that it is our research challenge.

II. THEORETICAL BACKGROUND OF NEAR-FIELD AND FAR-FIELD BEAMFORMING

A. Mathematical model of acoustic signal on microphone array in near field scenario

Suppose near-field signal scenario with M at the locations in 3D space denoted by set of vectors $\mathbf{r}_s^{(m)}; m = 1, M$. Time samples $x_p(n)$ of the signal on p-th microphone, in microphone array with P microphones on the locations denoted by the set of vectors $\mathbf{r}_p; p = 1, P$, can be expressed in the next form:

$$x_p(n) = \sum_{m=1}^{M} b_p^{(m)} s_0^{(m)}(n - \tau_p^{(m)}) + \eta_p(n) \tag{1}$$

where $b_p^{(m)}$ and $\tau_p^{(m)} = d_p^{(m)} / v = \left\|\mathbf{r}_s^{(m)} - \mathbf{r}_p\right\| / v$ denote attenuation and time delay of the m-th signal propagation from its source location to the p-th microphone. So it is Time Of Arrival -TOA based signal model.

Relative time delays can be expressed as:

$$\Delta\tau_{pq}^{(m)} = \Delta\tau_p^{(m)} - \Delta\tau_q^{(m)} = (\left\|\mathbf{r}_s^{(m)} - \mathbf{r}_p\right\| - \left\|\mathbf{r}_s^{(m)} - \mathbf{r}_q\right\|) / v \tag{2}$$

Time Difference Of Arrival TDOA model of the signal on microphone array can be formulated in spectral domain in such a way:

$$\mathbf{X}(k) = \mathbf{A}(k)\mathbf{S}_0(k) + \boldsymbol{\eta}(k) \tag{3}$$

where $\mathbf{X}(k)$ and $\boldsymbol{\eta}(k)$ denote vectors of the k-th spectral sample of the signal and noise spectrum respectively on microphone array, $\mathbf{A}(k)$ is a matrix whose columns are steering vectors whose elements have a general form:

$$a_p^{(m)} = b_p^{(m)} e^{-j2\pi k \Delta\tau_p^{(m)}/N} \tag{4}$$

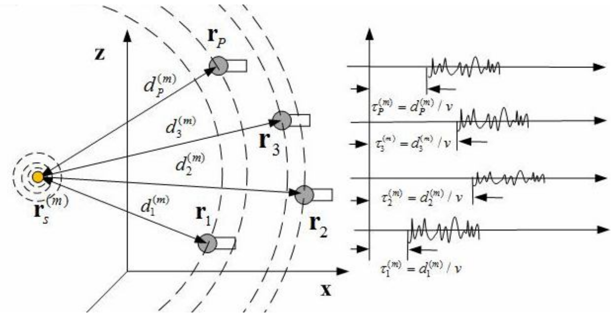

Fig.1 Near-field signal scenario

Elements of the vector $\mathbf{S}_0(k) = [S_0^1(k) \quad S_0^2(k) \quad \ldots \quad S_0^M(k)]^T$ are the k-th spectral samples of all M superposed acoustic signals on the sound source locations. It can be noticed that signal model given by (3) depends on the signal levels and source signal locations, regardless of far-field signal model, where there is a dependence of the signal model on Directions of Arrivals and signal levels in reference point (microphone) in space, so far-field signal model is basically TDOA base model. It can be noticed that steering vectors are frequency dependent so this model describe wideband nature of acoustic signals in array processing context.

B. Mathematical model of acoustic signal on microphone array in far-field scenario

Time samples $x_p(n)$ of the signal in far-field scenario on p-th microphone can be expressed as:

$$x_p(n) = \sum_{m=1}^{M} s_c^{(m)}(n - \Delta\tau_{cp}^{(m)}) + \eta_p(n) \tag{5}$$

where $\Delta\tau_{cp}^{(m)} = (\mathbf{k}^{(m)})^T \mathbf{r}_p / v$ denote relative propagation time delay of the m-th signal on the p-th microphone related to the referent point (microphone) in the space.

Vector $\mathbf{k}^{(m)}$ is unit vector represent direction of arrival (azimuth $\varphi^{(m)}$ and elevation $\theta^{(m)}$) of the m-th signal and it can be expressed as:

$$\mathbf{k}^{(m)} = -[(\cos(\theta^{(m)})\sin(\varphi^{(m)})\mathbf{i}_x + (\cos(\theta^{(m)})\sin(\varphi^{(m)}))\mathbf{i}_y + (\cos(\theta^{(m)}))\mathbf{i}_z \tag{6}$$

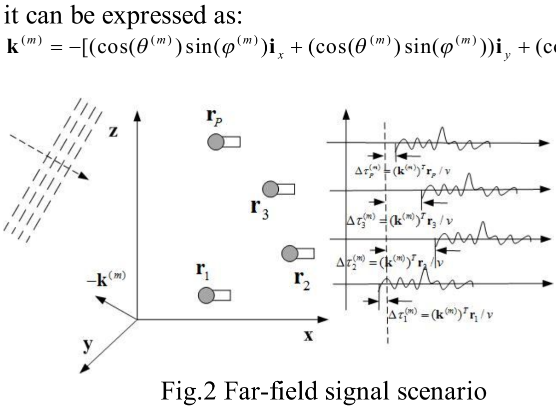

Fig.2 Far-field signal scenario

Time Difference Of Arrival TDOA model of the signal on microphone array can be formulated in spectral domain in such a way:

$$\mathbf{X}(k) = \mathbf{A}(k)\mathbf{S}_0(k) + \boldsymbol{\eta}(k) \tag{7}$$

where $\mathbf{X}(k)$ and $\boldsymbol{\eta}(k)$ denote vectors of the k-th spectral sample of the signal and noise spectrum respectively on microphone array, $\mathbf{A}(k)$ is a matrix whose columns are steering vectors whose elements have a general form:

$$a_p^{(m)} = e^{-j2\pi k \Delta\tau_{cp}^{(m)}/N} \tag{8}$$

Elements of the vector $\mathbf{S}_0(k) = [S_0^1(k) \quad S_0^2(k) \quad \ldots \quad S_0^M(k)]^T$ are the k-th spectral samples of all M superposed acoustic signals on the reference point (microphone) in the space.

So it can be seen that key differences of mathematical models of near and far-field signal scenario are related to the modeling of the propagation delays. Also, mathematical model of far-field signal scenario depends on the level of acoustic signal on the reference point in space so far-field beamforming provides relative level of acoustic power at the locations of the microphone array. However, mathematical model of near-field signal scenario depends on the level of acoustic signal on the sound location so near-field beamforming can provide direct estimation of the signal level at the location of acoustic source.

III. Generic versions of near-field and far-field Delay-and-Sum beamformers

From the array processing point of view acoustic signals has to be modeled as wideband signals, so acoustic beamforming is broadband beamforming and it can be basically implemented in spectral domain or in time domain with implicitly included some transformations in spectral domain. Generic versions of near-field and far field Delay-and-Sum beamformers are presented in the figures 3 and 4. Time delays in generic versions of beamformers can be realized in frequency domain using the following matrix transformation:

$$\mathbf{x}_p = \frac{1}{N}\sum_{m=1}^{M} (\mathbf{S}_0^{(m)}\mathbf{P}_p^{(m)}\mathbf{W}^H + \boldsymbol{\eta}\mathbf{W}^H) \tag{9}$$

where $\mathbf{x}_p$ denotes vector of time samples of the signal on the p-th beamformer finger, $\mathbf{P}_p^{(m)}$ denotes steering matrix with spectral elements of the steering vector of the m-th source on the p-th microphone and $\mathbf{W}^H$ is inverse FFT matrix.

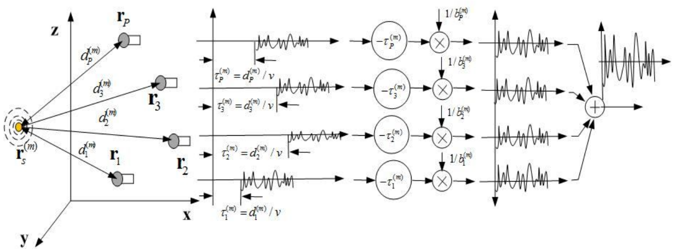

Fig.3. Generic version of near-field Delay-and-Sum beamformer

IV. Some experimental Results of acoustic near-field beamforming

Experiment was perfomed using measurement setup presented in the figure 5. which contains circular low-cost microphone array with diameter 0.75 m and 8 microphones in the array, multicahnnel microphone preamplifiers and signal acquisition and lap-top for the control of merasurement setup, collection of signal samples and off-line implementation of beamformers More detatils about this microphone array development platform are presented in [21].

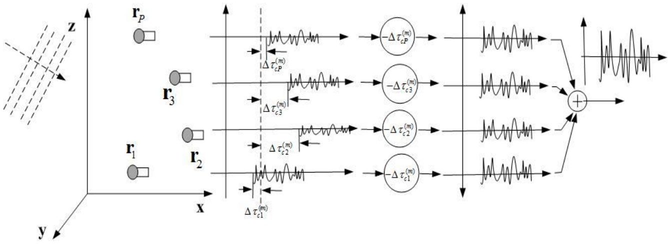

Fig.4. Generic version of far-field Delay-and-Sum beamformer

Acoustic signal (preamble of the IR UWB signal under standard 802.15.4a) is sequentially emitted form loud-speakers placed in near-field of the microphone array. Generic version near-field beamformer presented in the Fig.3. is applied for sound source localization. Results of sound localizations for loadspeakers are presented in the fig.6. Results of near-field localization of loudspeakers provided in MATLAB are overlayed with picture, realized with digital camera, from the position of the centre of microphone array.

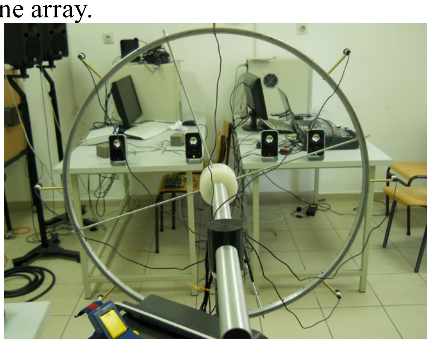

Fig.5. Measurement setup using circular microphone array

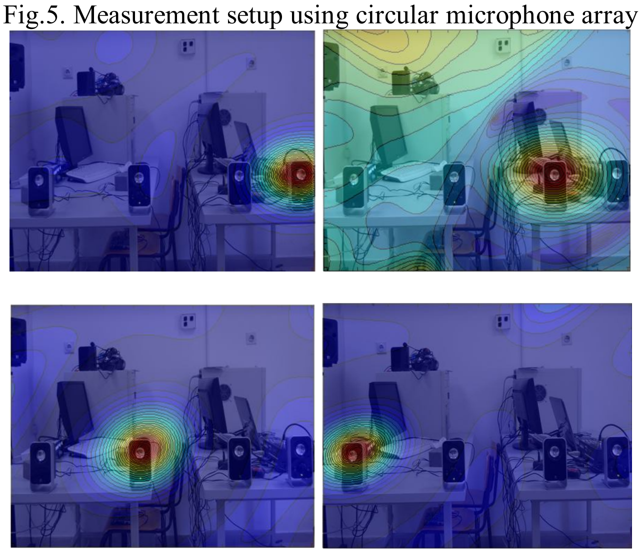

Fig.6. Results of localization loudspeakers by near-field beamforming

V. CONCLUSION

Application of near-field beamforming in acoustic cameras is the key research challenge since this kind of application is of a relatively new date. So the future research will be focused on the improvement of performances of the near-field beamforming regarding spatial resolution and dynamic range (side-lobe suppression). Some theoretical background of near and far-field beamforming is highlighted and generic version of near and far-field delay and sum beamformers are formulated. Presented experimental results prove that realized development platform with low cost microphone array and multichannel acquisition system is a good basis for future research.

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REFERENCES

[1] www.acoustic-camera.com
[2] www.lmsintl.com
[3] www.bksv.com
[4] www.norsonic.com
[5] www.microflown.com
[6] Ulf Michel, “History of acoustic beamforming”, Berlin Beamforming Conference (BeBeC) 2006, 21-22. Nov.2006
[7] S.Guidati, "Advanced beamforming techniques in vehicle acoustic", Berlin Beamforming Conference (BeBeC) 2010.
[8] C.Cariou, O.Delvedier "Localizing aircraft noise sources with large scale acoutic antenna" 27th International congress of the aeronautical sciences
[9] J.S.Pascal, J.F.Li "Use of double layer beamforming antenna to idetiy and locate noise in cabins, EURONOISE 2006, Finland
[10] S.C.Yu,T.W.Kim,A.Asada,S.Weatherwax,B.Collins,J.Yuh "Development of High-Resolution Acoustic Camera based Real-Time Object Recognition System by using Autonomous Underwater Vehicles", Proc.of the MTS/IEEE OCEANS 2006, Boston, Massachusetts, September 15-21, 2006
[11] "Battlefield Acoustic", Microflown ebook, chapter 21
[12] "Acoustic holography Noise Source identification and Quantification", LMS Application note.
[13] Joe C. Chen, Kung Yao, Ralph E. Hudson "Acoustic Source Localization and Beamforming:Theory and Practice", EURASIP Journal on Applied Signal Processing 2003:4, 359–370 Hindawi Publishing Corporation
[14] "Beamforming", Brüel&Kjar Technical Review, No.1. 204 available on site www.bksv.com
[15] F.Dablauwe, K.Jansen, M.Robin "Extending the usability of near-field acoustic holography and beamforming by using focalization, 14th International congress on Sound and Vibration, July 2007, Cairns, Australia
[16] "Near field Acoustic", Microflown ebook, chapter 8.
[17] "Far field Acoustic", Microflown ebook, chapter 9
[18] F.Dablauwe, K.Jansen, M.Robin," Combining acoustic imaging techniques to localize and identify sources", Berlin Beamforming Conference (BeBeC) 2008
[19] K.Haddad, J.Hald,"3D Localization of acoustic sources with spherical array", Acoustics'08,Paris, June 29- July 4. 2008
[20] M.Erić,A.Zejak,M.Obradović “Ambiguity Characterization of Arbitrary Antenna Array: Type I Ambiguity”, Fifth IEEE International Symposium on Spread-Spectrum Techniques and Applications, IEEE ISSSTA’98, Sun City, pp.399-402
[21] M.Mijić, D.Mašović, D.Šumarac Pavlović and M. Adnađević, "A Model of Planar Microphone Array Realized with Low-cost Multimedia Microphones", this conference
[22] B. Zimmermann, C. Studer, “FPGA-based Real-Time Acoustic Camera Prototype” Integrated Systems Laboratory ETH Zurich, 8092 Zurich, Switzerland
[23] J.Lanslot,F Deblauwe, K.Janssens," Sound Source Localization", INDUSTRIAL TECHNOLOGY • March 2011
[24] C.H.Jones, G.A.Gimour "Acoustic Camera Apparatus" United States Patent, Appl.No. 456.419, 5,August 1975.
[25] Y.A.Gurovich,K.J.Plotkin,D.H.Robinson,W.K.Blake,P.R.Donavan, "Acoustic Beamforming: Mapping Sources of Truck Noise", NCHRP report 635, National Cooperative Highway Research Program, Washington DC,2009.