Non-Stationary Random Wiener Signal Detection with Multistatic Acoustic System

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Abstract: The paper presents detection rule for multistatic reception of the non-stationary acoustic signal. The detection rule is obtained using maximum likelihood approach. Usually angular beam forming is applied to microphone array to localize spatially distributed emitters. In the paper, the time difference of arrival estimates of incoming acoustic emissions are used to localize their sources. The paper proposes wide frequency band acoustic noise source detection and localization enhancement using multistatic reception system. The paper shows experimental result on localization of source of wide frequency band emission by sound pressure imaging. All passband bandwidth of incoming signal is processed simultaneously. The localization is provided in range-cross range-elevation coordinates. The proposed technique may be suitable for 4D imaging in non-destructive testing and in ultra-wideband acoustic emitters' detection and localization. One of particular applications concerns testing of aircrafts landing regime and health monitoring of their engines at landing/take off.

1 INTRODUCTION

Detection rule is required to localize source of non-stationary random Wiener signal in range – cross range – elevation coordinates (Wentzell 1996, Levin 1969). The rule enables to define threshold level and the detector block diagram (Rozov 1987, Gusev 1988, Shirman 2007). Existing systems for acoustic noise source localization use pre-defined range to generate sound pressure images in cross range – elevation coordinates. As well, the systems generate conformal sound pressure images. The generation of those images uses beamforming techniques based-on estimates of phase difference of arrival of incoming signals in predefined frequency passband. The cited works do not contain detection of incoming signals. The paper presents rules for detection the signal against non-stationary random Wiener interference via bistatic and multistatic acoustic systems as well as corresponding threshold levels and block diagrams.

2 PROBLEM STATEMENT AND SOLUTION

Emission of an object is considered as a realization of non-stationary random Wiener signal. The signal frequency bandwidth is wide (Brüel & Kjær Sound and Vibration Measurement A/S 2009, Christensen and Hald 2004, Hald et al. 2004). Receivers and microphones limit it by their bandwidth B. The microphones are significantly spaced. Estimated parameter is time difference of arrival of incoming signal to the microphones. The pair of receivers' output signals are denoted as $y_I(t)$ and $y_{II}(t)$, correspondingly. The signals may contain the incoming signal (condition $A=1$) or not contain it (condition $A=0$) (Rozov 1987, Gusev 1988 and Shirman 2007).

The detection rule is derived for the incoming signal $x(t)$ against mix of interfering signals $c_I(t)$, $c_{II}(t)$ and intrinsic noise of microphones and receivers $n_I(t)$, $n_{II}(t)$. The intrinsic noises' power

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spectral density is N_0, for B of the equipment. The signal model is denoted as (Rozov 1987, Gusev 1988 and Shirman 2007):

$$\begin{gathered} y_I(t)=A\,x(t-t_x)+n_I(t)+c_I(t-t_c), \\ y_{II}(t)=A\,x(t-\tau)+n_{II}(t)+c_{II}(t-\tau), \\ 0<t<T \end{gathered} \tag{1}$$

where $x(t)$, $n_I(t)$, $n_{II}(t)$, $c_I(t)$ and $c_{II}(t)$ are not correlated in pairs; t_x and t_c are TDOA for the incoming signal and interference (industrial noise, multipath propagation on the scene etc.); τ is time delay that introduced to compensate the t_x; and T is acquisition time.

According to the Wiener process property, the considered $x(t)$, $n_I(t)$, $n_{II}(t)$, $c_I(t)$ and $c_{II}(t)$ have independent increments those obey normal distribution (Wentzell 1996, Levin 1969). The exact time interval, which enables to obtain the normal distribution of the increments, may be obtained by further experimental investigations.

The digital signal processing assumption enables to present the signals (1) as Kotelnikov series with constant interval $1/2B$ of time sampling. Elements of the $\vec{Y}$ are the noted above increments $\Delta y_{I,i}$ and $\Delta y_{II,i}$.

Probability densities of the $\vec{Y}$ are obtained for the two conditions: $A=1$ and $A=0$, in order to obtain likelihood ratio $L(\vec{Y})$ and the detection rule. At condition $A=1$, the incoming signal is correlated, as well as the interference. Joint probability density of corresponding samples $\Delta y_{I,i}$ and $\Delta y_{II,i}$ obeys two-dimensional distribution function of two normally distributed random variables (Levin 1969). The corresponding probability density function is obtained based-on following equality:

$$p(\vec{Y}/A=1)=\prod_{i=1}^{k} p(\Delta y_{I,i}, \Delta y_{II,i} / A_i = 1),$$

where $k=2BT$. At the condition $A=0$, the probability density function is obtained similarly. At the latter condition, no elements of the $\vec{Y}$ are correlated, except the interference. Relation of $p(\vec{Y}/A=1)$ to $p(W/A=0)$ is the likelihood ratio. For the technical implementation, natural logarithm of the obtained $L(\vec{Y})$ is more appropriate. One assumes that variances of increments of the noise and the interference are larger than variance of increments of the signal. Thereat, one of addends of the obtained expression do not depends on the incoming signal. The addend defines the threshold level. Assumption that variances of increments of the noise are larger than variances of the interference enables to obtain weight of the integration in the expression. The obtained detection rule estimates autocorrelation functions of increments of signals (1) and their cross-correlation function. Only the latter depends on time difference of arrival of incoming signal. Thus, the detection rule envisages calculating the expression:

$$Z_1 \approx \int_0^T k_I \Delta y_I(t)\; k_{II} \Delta y_{II}(t)\, dt \tag{2}$$

where $k_{I,\,II}$ define gain values for receivers 1 and 2, correspondingly; $\Delta y_{I,\,II}(t)$ define increments of the signals (1).

The rule for non-stationary random Wiener signal detection in bistatic reception system is obtained (Fig. 1, baseline 1).

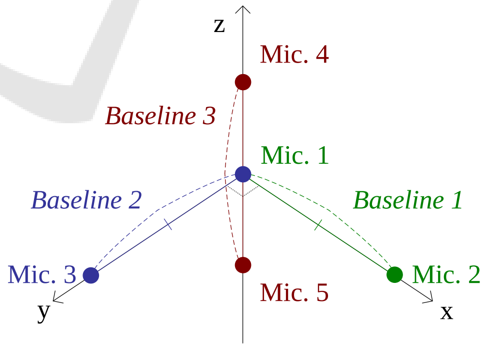


Figure 1: Basic geometry of the multistatic acoustic system.

The detection rules for other baselines (Fig. 1) may be expressed similarly to (2). Output signals of the bistatic reception systems are denoted as $u_1(t)$, $u_2(t)$ and $u_3(t)$, correspondingly.

The further detection rule obtainment is similar to the above one. But, the new $\vec{Y}$ consists of $u_1(t)$, $u_2(t)$ and $u_3(t)$ samples. The samples are denoted as $u_{1,i}$, $u_{2,i}$ and $u_{3,i}$. At the condition $A = 1$, the signal and interference components of the $\vec{Y}$ are correlated in pairs. Joint probability density of corresponding samples $u_{1,i}$, $u_{2,i}$ and $u_{3,i}$ obeys distribution function of normally distributed random variables (Levin 1969). At the condition, the corresponding probability density function is obtained based-on following equality:

$$p\left(\vec{Y} / A = 1\right) = \prod_{i=1}^{k} p\left(u_{1,i}, u_{2,i}, u_{3,i} / A_i = 1\right).$$

At the condition $A = 0$, the samples of $\vec{Y}$ are independent. Variations of these samples are same. Relation of the latter probability density functions is the new likelihood ratio $L\left(\vec{Y}\right)$. One of addends of the obtained ratio defines the threshold level, as the signal power in the multistatic system is low. Other one addends sum of power estimates from the three considered bistatic systems (Fig. 1). All possible cross-baseline cross correlation functions are subtracted from the latter addend. The last addend provides multiplication of power values of output signals of the bistatic systems. The latter is agreed to detection quality at limited number of samples (Shirman 2007). The input signals squaring is valuable for small signal-to-noise-plus-interference ratio at outputs of the bistatic systems. Spatial localization of the emission source is utilized by the considered multistatic system (Fig. 1) by the latter addend:

$$Z_{123} \approx \int_0^T k_1 u_1^2(t)\, k_2 u_2^2(t)\, k_3 u_3^2(t)\, dt \qquad (3)$$

where k_i are gain values of corresponding bistatic systems 1-3. All intermediate results and threshold level expression were dropped down.

The obtained requires to estimate TDOA of the signal by each bistatic system and to provide further calculation according to (3), for each node of spatial grid.

The non-stationary random Wiener signal detection rule for three bistatic systems is obtained according to the maximum likelihood method with respect to the threshold level.

3 EQUIPMENT OF THE ACOUSTIC CAMERA

Acoustic camera, manufactured by Brüel & Kjaer (Sound and Vibration Measurement A/S) is used. The camera uses 18 microphones type 4958, 12-channel and 6-channel input modules type 3053-B-120 and 3050-B-060, correspondingly. The acoustic camera includes Pulse LabShop software. The latter was used to transfer the multichannel equipment output signals for further post-processing.

The microphones dimensions are: 34 mm long, 7 mm diameter. Sensitivity of the microphones is 11.2 mV/Pa. Operating temperature range of the microphones is from 10˚C to +55˚C. The microphones dynamic range is from 28 dB to 140 dB. The microphones have CCLD preamplifier with transducer electronic datasheet (TEDS - IEEE 1451.4 V.1.0).

Both input modules support TEDS transducers and deliver REq-X technology, which flattens the transducers frequency responses by “mirroring” them. These input modules are mounted in 5-slot Mainframe LAN-XI type 3660-C-000 with battery module type 2831. The 3050-B-060 input module delivers Dyn-X technology that expands its dynamic range depending on exact signal quantization and bandwidth.

The acoustic camera upper frequency is 25.6 kHz and its quantization rate is about 65 kHz. The signals are synchronized using IEEE 1588 Precision Time Protocol.

The camera calibration may be provided in advance to assure precision of sound pressure estimates. The acoustic camera incudes hardware and software for the calibration. The portable calibrator is battery operated. The calibration frequency is 251.2 Hz. Pistonphone calibrator type 4228 with external barometer satisfies ANSI S1.40-1984 and IEC 942 (1988) Class 0L. The calibrator has following adaptors: DP-0775 for sequential calibration of the microphones and adaptor WA-0728-W-003 for calibration of groups of 6-microphones. The calibrator can be used over a wide range of temperature, humidity and pressure while still maintaining high accuracy.

Optic camera with resolution 640×480 pixels and microphones in 0.33 m slice wheel array of the acoustic camera are mounted on 3D tripod head

Manfrotto 229 and tripod Manfrotto 058B. The load capacity of both head and tripod is 12 kg (safety payload).

The acoustic camera data transfer cables limit spatial separation between the equipment blocks. The acoustic camera consists of three main blocks: a microphone array with optic camera, input modules in a frame and a laptop with software. Cable harness type WL1297-W-004 2013W21 with length ~4.5 m limits separation between the microphone array and the mainframe. Both optic camera USB cable with length ~6.3 m and LAN cable type AO1450-D-020 2013W13 with length ~2 m limit separation between the mainframe and laptop with the acoustic camera software. The main features of the laptop type 7201-E-GB2 (Dell Latitude E6430) are listed below: E6430 CPU, 6 GB RAM, 1 TB HDD, Wi-Fi, Ethernet 1 Gb, DVD-RW.

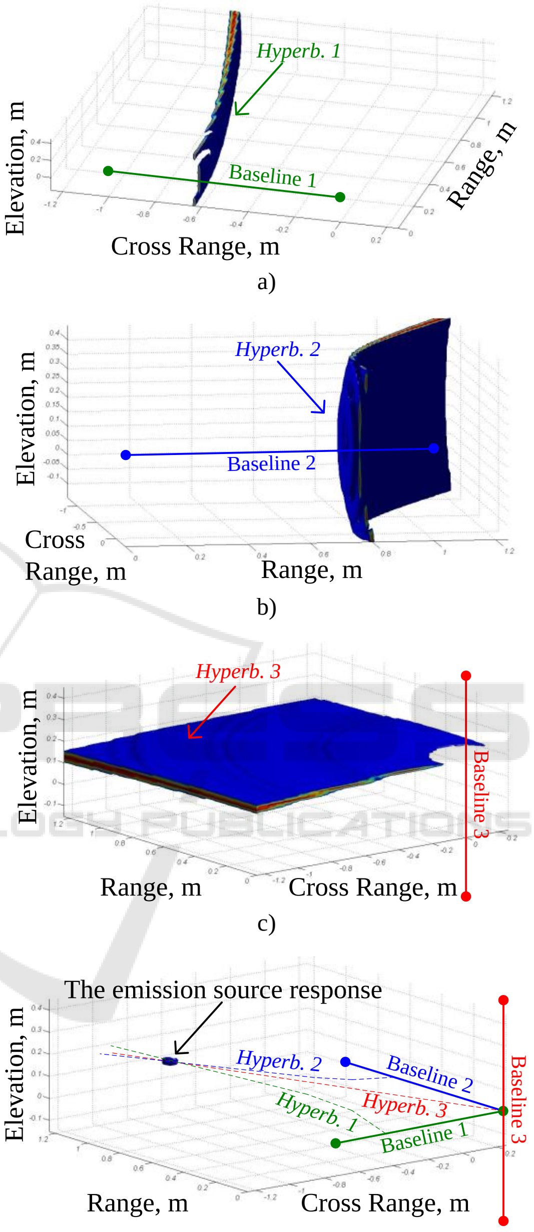
The acoustic camera hardware and software modules are supplied with full documentation (instruction manual, specifications). Acoustic images may be generated using Array Acoustics Post-processing (Version 17.1.2.308). Measurement data may be collected using Pulse LabShop (Customized Solution Version 17.1.2). Other existing software and drivers are not listed in this work.

4 DETAILS AND RESULT OF EXPERIMENT

Experiment is focused on localization of acoustic noise emission source with the multistatic system (Fig. 1). Microphone 1 is placed in the origin of Cartesian coordinate system. Baselines equal to 1 m. Emitter coordinates in the field of view are as following: range 1 m, cross range -0.8 m and elevation 0.15 m. Center frequency of the incoming signal is about 5 kHz and bandwidth of the signal is about 10 kHz. The latter corresponds to TDOA resolution of about 3.5 cm, at a baseline.

The signal processing contains multiplication of the bistatic systems output signals normalized squared. The amplitude calibration of the Acoustic Camera was carried out in advance. Obtained results are displayed in logarithmic scale (Fig. 2). Multipath propagation inside a typical office room affects equality of responses of the bistatic systems. Thus,– 6 dB threshold is applied to the results. The normalization is not present in (3). Slight irregularity of responses of three bistatic systems (Fig. 2) is affected by insufficiently small pixel size.

The result shows opportunity to localize the emission source with the presented approach (3).



a)

b)

c)

d)

Figure 2: Acoustic images generated using the shown bistatic systems and according to the proposed approach using the multistatic system.

5 CONCLUSIONS

Newly developed detection rules of non-stationary random Wiener signal against such interference are proposed for bistatic and multistatic acoustic systems. The rules enable to define corresponding threshold levels and technically feasible block diagrams. The four-site system is considered for spatial localization of acoustic emission source. The proposed approach uses time difference of arrival estimates of incoming signal instead of its phase difference of arrival estimates to localize the source. Test source passband bandwidth about 10 kHz is processed simultaneously, in the experiment. Further implementation of the approach is promising for wideband acoustic noise source localization.

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