Non-stationary Random Wiener Signal Detection Rule for Case of Multistatic Reception

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Abstract. The paper presents detection rule for multistatic reception of non-stationary acoustic signals. The detection rule is obtained using maximum likelihood approach. Usually microphone array localizes spatially distributed emitters by angular beam forming. In the paper, the time difference of arrival estimates of incoming acoustic emissions are used for the localization. The paper shows experimental result on localization of source of wide frequency band emission by sound pressure mapping. The paper proposes wide frequency band acoustic noise source detection and localization enhancement using multistatic approach.

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 mapping in non-destructive testing and in ultra-wideband acoustic emitters' detection and localization. One of particular applications concerns testing of aircraft's landing regime and health monitoring of the aircraft's engines at its landing/take off.

1 Introduction

Detection rule is required to localize source of non-stationary random Wiener signal in range – cross range – elevation coordinates [1-2]. The rule enables to define threshold level and the detector block diagram [3-5]. Existing systems for acoustic noise source localization use pre-defined range to generate sound pressure maps in cross range – elevation coordinates. 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

Let us consider emission of an object as a realization of non-stationary random Wiener signal. The signal frequency bandwidth is wide [6-8]. Receivers and microphones limit it by their bandwidth B. The microphones are significantly spaced. Estimated parameter is time difference of arrival (TDOA) 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 $A = 0$) [3-5].

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 spectral density is N_0, for B of the equipment. The signal model is denoted as [3-5]:

$$\begin{aligned} y_I(t) &= A\,x(t - t_X) + n_I(t) + c_I(t - t_C), \\ y_{II}(t) &= A\,x(t - \tau) + n_{II}(t) + c_{II}(t - \tau), \quad 0 < t < T \end{aligned} \tag{1}$$

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; 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 [1, 2]. 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 $(2B)^{-1}$ of temporal 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 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 [2]. 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, all elements of the $\vec{Y}$ are not 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. Further obtainment of the detection rule is done based-on physically existing assumptions on relations between variance of increments of signal, interference and noise. They enable to express weight of integration, the threshold level and to define the addend that depends on TDOA. The obtained detection rule estimates cross-correlation function of increments of signals (1). The rule for non-stationary random Wiener signal detection in bistatic reception system is obtained.

The detection rules for other baselines may be expressed similarly. 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 requires 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 [2]. At the condition, the corresponding probability density function is obtained based-on same approach. 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 $L(\vec{Y})$. One of addends of the obtained ratio defines the threshold level, as the signal power in the multistatic system is low. Two other one addend depend on power estimates of the three considered bistatic systems and cross-baseline cross correlation functions. 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 [5]. 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 by the latter addend:

$$Z_{123} \approx \int_0^{T_H} \left\{ \left[k_1 u_1^2(t) \right] \left[k_2 u_2^2(t) \right] \left[k_3 u_3^2(t) \right] \right\} dt \qquad \textbf{(2)}$$

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 (2), 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 Test Measurement Scenario and Result

The indoor experiment is focused on localization of noise emission source with the considered multistatic system. Each baseline equals to 1 m. Single target is placed in the field of view. Its coordinates are as following: range 1 m, cross range -0.8 m, elevation 0.15 m. The incoming signal bandwidth is limited in the equipment. The center frequency is about 5 kHz. The bandwidth is about 10 kHz. The latter corresponds to TDOA resolution of about 3.5 cm, at a baseline. Acoustic camera, manufactured by Brüel & Kjaer is used. The camera uses microphones type 4958.

The obtained result shows possibility to localize emission source with the presented approach (2).

4 Conclusions

Newly developed detection rules of non-stationary random Wiener signal against such interference are proposed for bistatic and multistatic acoustic systems. The corresponding threshold levels and technically feasible block schemes are given. Spatial localization is performed in the considered four-site system. In the experiment, the test source passband bandwidth about 20 kHz is processed simultaneously. The system localizes objects based-on time difference of arrival estimates of their signals instead of frequently used phase difference of arrival estimates. Implementation of the proposed approach is promising for acoustic noise source localization.

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