DETECTION OF BROADBAND SIGNALS IN THE FIELD OF APERTURE AND ARRAY SYSTEMS

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Antennas and antenna arrays in low band underwater systems introduce significant linear distortions that affect the detection of broadband signals. The article gives an analysis of the distortions using the space-time impulse response method. The signal received at different directions is subjected to two types of filtration, one matched to the transmitted signal and another one matched to the distorted signal. For the purpose of the simulation the Matlab software was used. Detection performance can be greatly enhanced, if receiver design takes account of the distortions.

INTRODUCTION

The frequency of signals is an important factor that affects the transmission performance of underwater communication systems. Although low band signals have a typically low attenuation and a substantial range, the transmission rates are limited. Higher frequency signals, on the other hand, allow better transmission rates, but because of a stronger attenuation, the signal to noise ratio suffers.

Channel induced linear distortions have an effect on the shape of the signal and the detection performance. To optimise the use of the channel and improve transmission rate, it is important to understand how the distortions are created. The range and transmission of underwater communications systems can be improved by adapting advanced transmission techniques used in telecommunications modems, truly broadband devices. The idea is that the techniques should allow a better match of the parameters of the devices to the characteristics of the underwater channel, such as deflections, reflections, multi-path transmission, all of which cause strong the signal level fluctuation. The result is the linear distortion changeable over time and affecting the shape of the received signals, and consequently the detection performance.

The article presents a method of analysis of the effects of linear distortions on reception in an ideal channel where the broadband signal distortions are created mere in the acoustic field of the directional antennas [4].

Section one gives a description of the broadband signal detection using matched reception. The receiving filter can be changed to be matched either to the transmitted signal or to the distorted signal at the receiver input. Section two gives a description of the acoustic field in the broadband terms where the frequency transfer functions are determined using the space-time aperture impulse responses. Section three presents the simulations applied using a model of communications system with a matched reception, implemented in the Matlab software. The differences of the detection performance are presented in the cases of the reception matched to the original signal and to the distorted one.

1. RECEPTION OF BROADBAND SIGNALS

Detection of a known signal means that the signal presence or absence must be identified at the receiver output. Where time limited signals are concerned, i.e. signals carrying digital information or echolocation signals, it is recommended to use filtration to maximise the signal to noise ratio at the receiver output. For the signal $s(t)$ involving the white noise distortions, the optimum linear filter is the matched filter [1, 2] whose the transmission function $H(\omega)$ meets the condition:

$$H(\omega) = A \cdot S^*(\omega)\exp(-j\omega t_0), \tag{1}$$

where: A – the constant coefficient, $S^*(\omega)$ – the complex conjugate spectrum of the signal $s(t)$, t_0 – the signal duration. The impulse response $h(t)$ of the filter comes as:

$$h(t) = s(t_0 - t), \tag{2}$$

which means that the received signal is time reversed and delayed by t_0. The signal $y(t)$ at the receiving filter output is a convolution of the signal $s(t)$ and the response $h(t)$:

$$y(t) = A\int_0^t s(\tau)s[\tau - (t - t_0)]\, d\tau = A \cdot c_s(t - t_0) \tag{3}$$

and comes as the auto-correlation function $c_s(t)$ of the input signal $s(t)$ delayed by t_0 – the maximum signal value $y(t)$ is for $t = t_0$. The spectrum of the output signal has the following form:

$$Y(\omega) = A|S(\omega)|^2. \tag{4}$$

The matched reception is analysed in a system illustrated in Figure 1. The broadband input signal $s_s(t)$ with the spectrum $S_s(\omega)$ goes through the transmission channel described with the impulse response $h_c(t)$ and the frequency transfer function $H_c(\omega)$. At the channel the output signal $s_c(t)$ is described with convolution: $s_c(t) = s_s(t) * h_c(t)$.

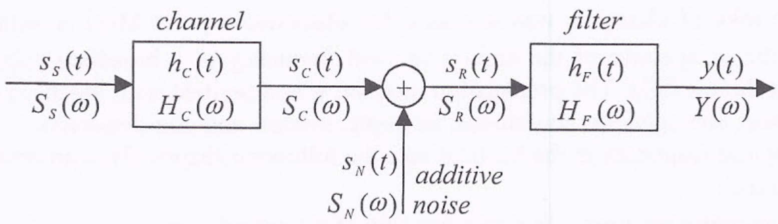

Figure 1. Model of a communications system.

The interference is then added to the signal $s_N(t)$ as AWGN (additive white Gaussian noise). The received signal $s_R(t) = s_C(t) + s_N(t)$ which the spectrum is $S_R(\omega)$ undergoes the receiving filtration. At the output of the filter with the impulse response $h_F(t)$ and the transfer function $H_F(\omega)$, the result is the signal $y(t)$ which can then undergo the detection by comparing it with the threshold value.

In this article the filter in the receiver was matched to the signals $s_S(t)$ and $s_C(t)$. The impulse response $h_F(t)$ was given these forms accordingly:

$$h_{FS}(t) = s_S(t - t_0) \qquad \text{and} \qquad h_{FC}(t) = s_C(t - t_0), \tag{5}$$

The result were two output signals:

$$y_S(t) = s_S(t) * h_S(t) \qquad \text{and} \qquad y_C(t) = s_C(t) * h_C(t). \tag{6}$$

2. CHANNEL TRANSFER FUNCTION

The distortions introduced by the directional antennas can be effectively analysed by using the space-time aperture impulse response method [5, 6]. The impulse response is a function of time which changes as the observation point and the aperture location change. It gives an almost direct reproduction of the geometrical parameters of the acoustic system, transforms them into delays and changes signal size.

Figure 2 presents a single dimension aperture radiating in an acoustic medium in two versions – continuous and discrete. In the first case it comes as a radiating line uniformly excited whose length is a, and in the latter as set N of identical point sources spaced at $d = a/\mathrm{N}$.

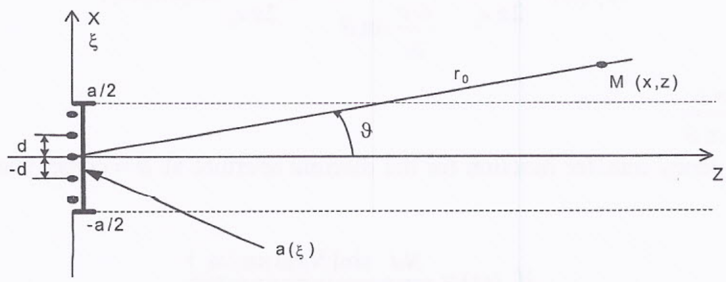

Figure 2. The geometry of the radiating systems: continuous aperture at length a and discrete aperture with N sources, $d = a/N$; $\mathrm{M}(\vec{x})$ - observation point, $\vec{x} = (x, z) = (r_0, \vartheta)$, $a(\xi)$ - distribution of the excitation.

For the sake of clarity, it was assumed that observation point $M(\vec{x})$ is within an area which from the perspective of the highest spectral frequency of a broadband signal can be considered as the far field. The propagation medium was described with idealised properties, i.e. as unlimited, homogenous, continuous, isotropic, lossless and non-dispersive.

The Impulse responses in the far field take the following shapes [3] in an established direction $\vartheta = const$:

- for the continuous aperture it is a gate function of a constant size:

$$h_C(\vartheta,t) = \begin{cases} \dfrac{a}{2\pi r_0}\delta(t-t_0) & for\ \ \vartheta = 0, \\ \dfrac{c}{2\pi r_0|\sin\vartheta|}\, rect\left(\dfrac{t}{t_a|\sin\vartheta|}\right) * \delta(t-t_0) & for\ \ \vartheta \neq 0, \end{cases} \tag{7}$$

where: $t_a = a/c,\ t_0 = r_0/c$.

- for an aperture consisting of several source points, it is a series of N impulses of a constant value and constant time delay dependent on the observation direction.

$$h_C(\vartheta,t) = \frac{a}{2\pi r_0}\sum_{i=-\frac{N-1}{2}}^{\frac{N-1}{2}} \delta\left(t - \frac{r_0 - id\sin\vartheta}{c}\right). \tag{8}$$

On the main direction, the impulse responses in both cases come as the single impulses. When the observation angle changes, the impulse response becomes the gate function for the continuous aperture and the series of impulses for the discrete aperture.

The Fourier transform of the impulse response $H(\vartheta,\omega)$ is a function of the observation direction and frequency. It can be interpreted as a generalised transfer function of the radiating aperture-observer system which for an established frequency takes the form of the directivity patterns and for an established direction – that of the frequency transfer function [1] which characterises the linear distortions of the broadband signals in the acoustic field. For the continuous aperture the frequency transfer function for $\vartheta = const$ has the following form:

$$H_c(\omega) = \frac{a}{2\pi r_0}\frac{\sin\left(\dfrac{\omega a}{2c}\sin\vartheta\right)}{\dfrac{\omega a}{2c}\sin\vartheta} = \frac{a}{2\pi r_0} Sa(\pi\omega/\omega_0), \tag{9}$$

where $\omega_0 = \dfrac{2\pi c}{a\sin\vartheta}$.

The frequency transfer function for the discrete aperture at $\vartheta = const$ takes the following form:

$$H_c(\omega) = \frac{Nd}{2\pi r_0}\frac{\sin(N\pi\omega\,\pi\omega/\omega_0)}{N\sin(\pi\omega\,\pi\omega/\omega_0)}. \tag{10}$$

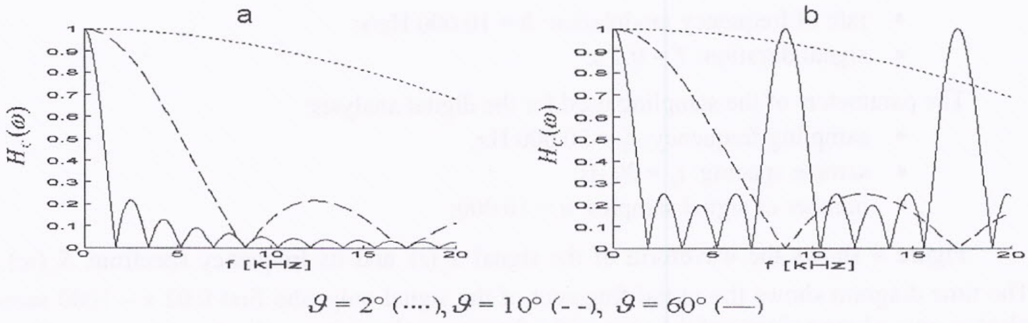

Figure 3. The shape of the transfer function $H_c(\omega)$ on the selected observation directions for the continuous aperture (a) and discrete aperture (b).

Figure 3 shows an example of the effect the observation direction has on limiting the transfer band where radiation in water is concerned for the continuous aperture $a = 1$ m and discrete aperture $N = 5$. The distortions in the case of the continuous aperture (Fig. 3a) mean the low band filtration. The sense of the parameter ω_0 from formula (9) is the pulsation for which the transfer function takes the first zero. For the discrete aperture (Fig. 3b) the transfer function for the small angles ($\vartheta = 2°$, $10°$) is the same as for the continuous aperture, and for the bigger angles ($\vartheta = 60°$) the comb-shaped filtration effects are clearly visible.

An important thing is that function $H(\vartheta, \omega)$ gives a mathematical description of the angular and frequency relations in a similar and quasi-symmetric way. This is not to say, however, that the directional properties of the antennas for the broadband signals can be expressed similarly to the directivity patterns defined for the monochromatic signals [4].

3. COMPUTATIONAL SIMULATION OF RECEPTION

The relations given in sections 1 and 2 were the basis for the computational simulations of the signal filtration for two cases of reception: on the antenna's main direction and at 60 degrees. The computations were made using Matlab 6.5 for both systems of the radiation as given in Figure 2 – the continuous and discrete aperture.

The impulse response and the transfer functions were determined for the each observation direction treated as a transmission channel with a deterministically assigned frequency and time properties.

In order to examine the broadband properties of the channels, the signal used had a relatively slow linear frequency change (the so called chirp):

$$s_S(t) = \sin\left(2\pi b t^2\right), \tag{11}$$

where b – the rate of the frequency change in [Hz/s]. The signal allows the transfer function to be measured by the way of wobbulation – the envelope of its waveform is a reflection of the signal spectrum.

For the purpose of the simulation, the following parameters were introduced for the input signal $s_S(t)$:

- maximum frequency in signal spectrum: $f_{max} = 4\,000$ Hz;
- minimum frequency in signal spectrum: $f_{min} = 0$ Hz;
- signal bandwidth: $B = 4\,000$ Hz;

- rate of frequency modulation: b = 10 000 Hz/s;
- signal duration: T = 0.2 s.

The parameters of the sampling used for the digital analysis:

- sampling frequency: f_p = 50 000 Hz;
- sample spacing: t_p = 20 µs;
- number of signal samples: n = 10 000;

Figure 4 shows the waveform of the signal $s_S(t)$ and its frequency spectrum $S_S(\omega)$. The time diagram shows the initial fragment of the signal only (the first 0.02 s – 1000 samples) to give a better clarity of the type of the frequency changes over time.

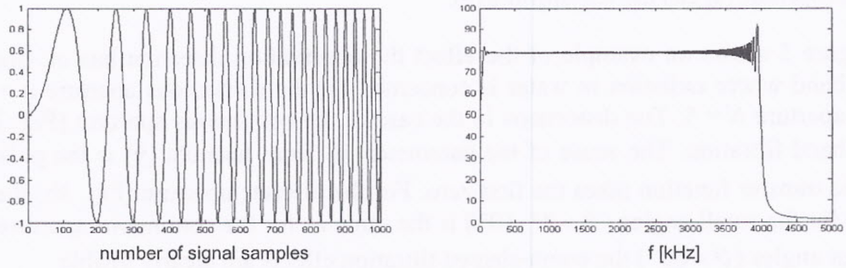

Figure 4. The "chirp" signal - (a) the time form $s_S(t)$ and (b) the frequency spectrum $S_S(\omega)$.

The form of the signal $y(t)$ received at the output varies depending on the impulse response of the receiving filter. Figures 5a and 5b show the signal $y(t)$ when the channel does not introduce any distortions to the signal $s_S(t)$ (the reception along the main axis) and when no noise is present. The received signal is equal to the transmitted one $s_R(t) = s_S(t)$ and the output signal $y(t)$ which undergoes detection is a function of the auto-correlation of the transmitted signal. This is true both for the continuous and discrete apertures.

Figure 6 shows the same output signal with AWGN interference present $s_N(t)$ with two power levels: S/N = 0 dB (Fig. 6a) and S/N = -25 dB (Fig. 6b).

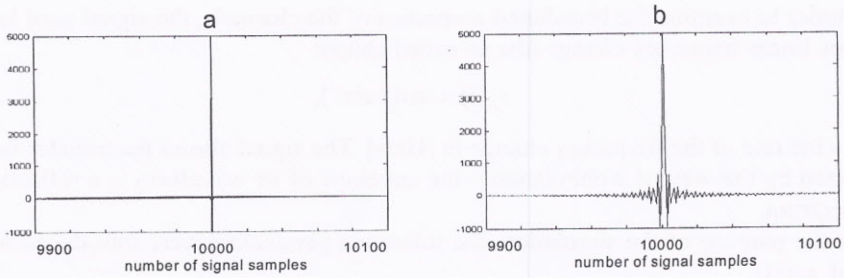

Figure 5. Auto-correlation function of the transmitted signal with no distortion or interference; (a) entire waveform, (b) fragment of the central part.

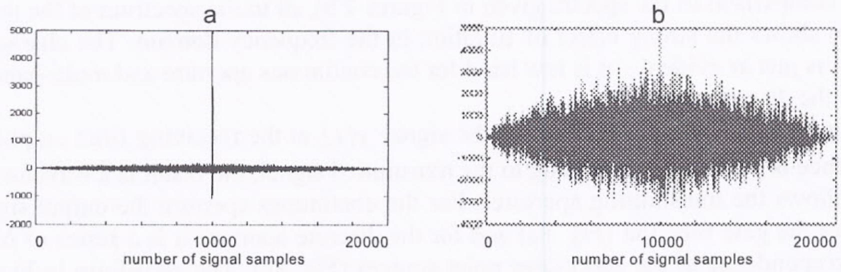

Figure 6. Mutual correlation functions of the signal received along the antenna's main axis (ϑ=0°) and the transmitted signal: (a) S/N = 0 dB and (b) S/N = -25 dB

The simulation of the matched reception in the direction $\vartheta \neq 0°$ was made for two situations – one when the channel transfer function $H_C(\omega)$ is unknown and the second one, when the transfer function is known. The signal waveforms $s_R(t) = s_C(t) + s_N(t)$ underwent the reception filtration under the following two assumptions:

1. the filter in the receiver is matched to the transmitted signal $s_S(t)$;
2. the filter in the receiver is matched to the expected signal $s_C(t)$.

Figure 7 shows the shape of the linear distortions introduced to the input signal $s_S(t)$. The signal $s_C(t)$ in the field of the continuous aperture and its frequency spectrum are shown in Figures 7 a), b) and the signal $s_C(t)$ in the field of a five-element discrete aperture is given in Figures 7 c), d). The shape of the envelope of the signal waveform at the channel output follows the transfer function $H_C(\omega)$ of the channel which is illustrated in Figures 7 a), b) and 7 c), d) .

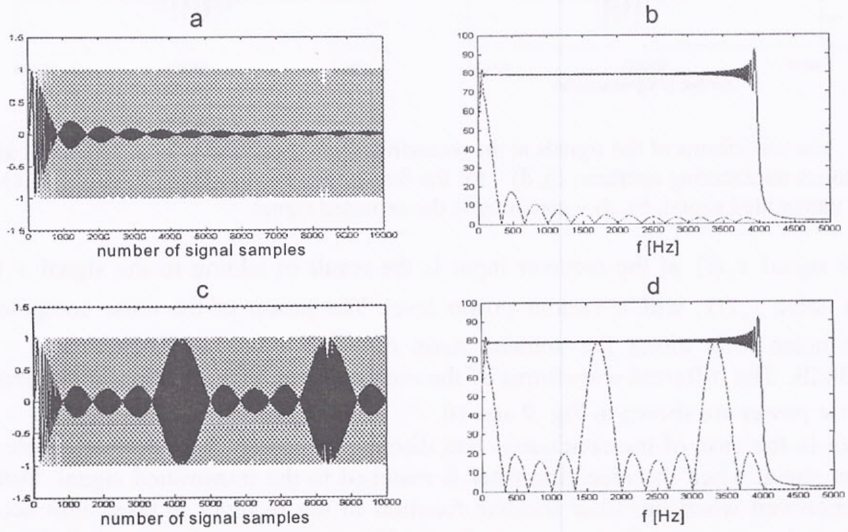

Figure 7. The waveforms (a, c) and the frequency spectra (b, d) of the signals at the receiver output observed at ϑ=60°; a), b) – the continuous aperture; c), d) – the five element aperture; (the transmitted signal in the background).

A comparison of the spectra given in Figures 7 b), d) to the spectrum of the input signal (Fig. 4b) shows the strong effect of filtration in the frequency domain. The character of the filtration is just as evident – it is low band for the continuous aperture and multi-bands (comb-like) for the discrete aperture.

Figure 8 shows the waveform of the signal $y(t)$ at the receiving filter output when no interference is present. By matching to the transmitted signal, the result is a waveforms whose shape follows the transmitting apertures. For the continuous aperture the output signal shape resembles the gate function (Fig. 8a) and for the discrete aperture it is a series of N impulses that correspondence to the successive point sources (Fig. 8c). The waveform in Figures 8 b), d) are the auto-correlation functions of the received signal where the shape follows the spatial function of the aperture auto-correlation.

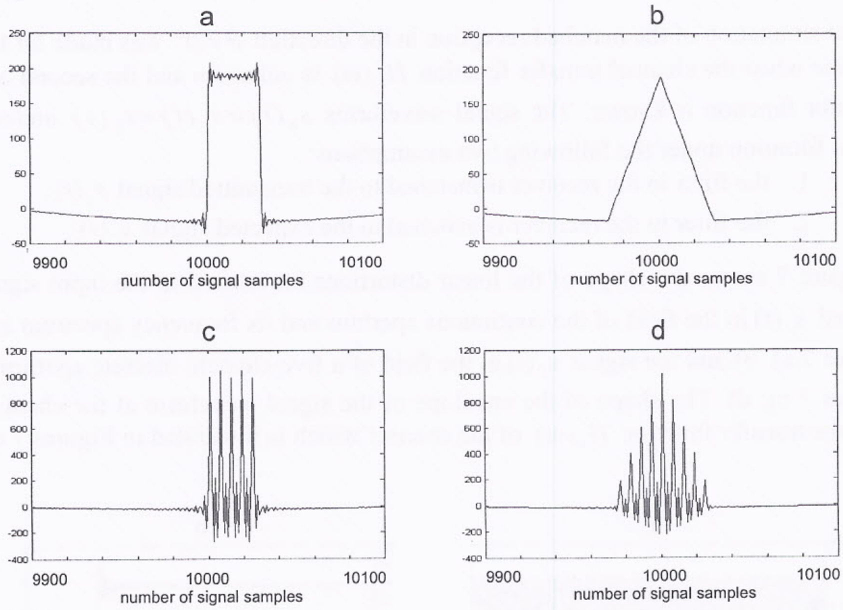

Figure 8. The waveforms of the signals at the receiving filter output (no noise in channel): a), b) – for the continuous transmitting aperture; c), d) – for the five-element transmitting aperture; a), c) – matching to the transmitted signal; b), d) – matching to the expected signal.

The signal $s_R(t)$ at the receiver input is the result of adding to the signal $s_C(t)$ white Gaussian noise $s_N(t)$, with a various power level. The power of the noise computed as the signal to noise ratio along the antenna main direction was varied from S/N = 0dB to S/N = - 30dB. The different waveforms of the output signal $y(t)$ for the two different levels of the noise power are shown in Fig. 9 and 10.

Both in the case of the continuous and discrete apertures, there is much more noise in the output signal when the receiving filter is matched to the transmitted signal. Detection is greatly improved when the filter transfer function in the receiver is takes into account the channel impulse response. Once a certain limit of the noise power is exceeded, the signal detection is almost impossible (Fig. 10). By matching to the expected signal, the noise power limit is increased of about 5-10 dB.

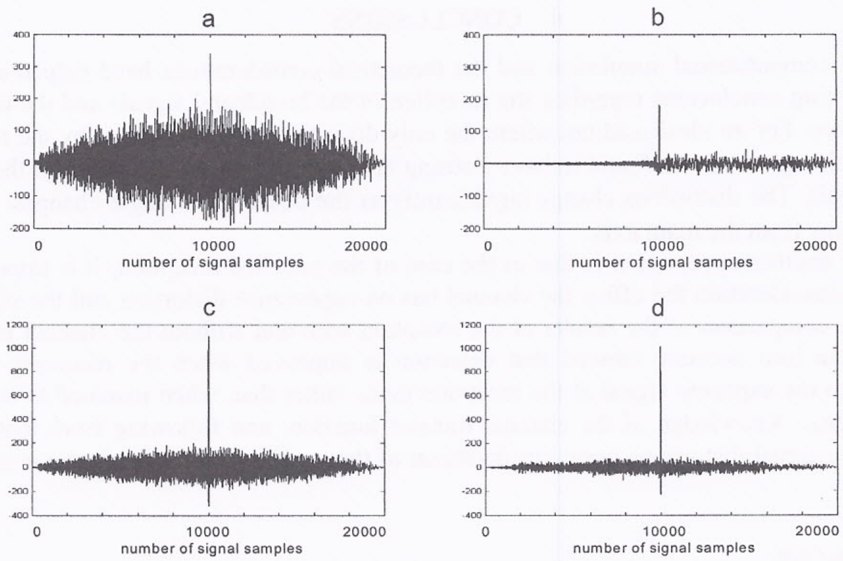

Figure 9. The waveforms of the signals at the receiving filter output (the noise in the channel S/N=0 dB): a), b) – for the continuous transmitting aperture; c), d) – for the five-element transmitting aperture; a), c) – matching to the transmitted signal; b), d) – matching to the expected signal.

The signal to noise ratio at the angle $\vartheta = 60°$ to the main axis by (compare Fig. 6) gets worse as a result of the signal distortions (the signal energy is filtered). The result is a much lower noise power limit in the case of the reception on main axis.

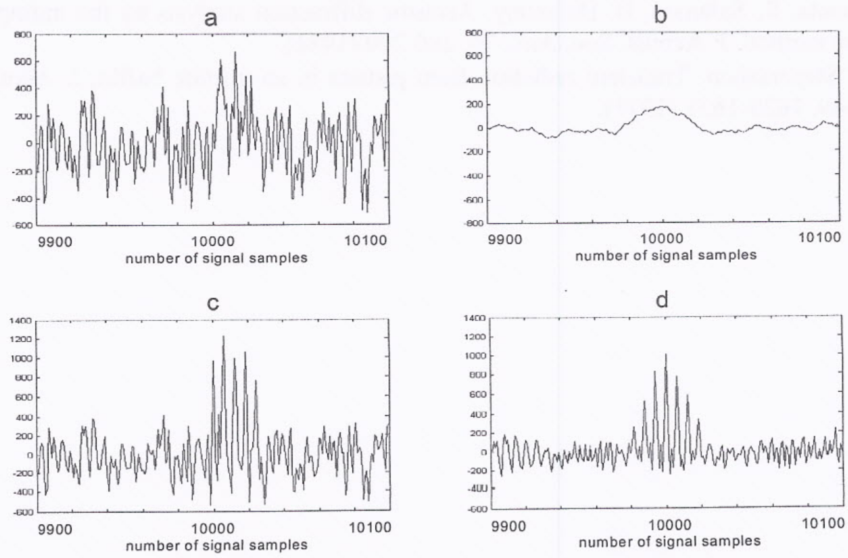

Figure 10. The waveforms of the signals at the receiving filter output (the noise in the channel S/N=-10 dB): a), b) – for the continuous transmitting aperture; c), d) – for the five-element transmitting aperture; a), c) – matching to the transmitted signal; b), d) – matching to the expected signal.

4. CONCLUSIONS

The computational simulation and the theoretical considerations have helped arrive to the interesting conclusions regarding the reception of the broadband signals and the detection performance. For an ideal medium where the only distortions are introduced by the radiation aperture, the aperture was found to have a strong effect on the linear distortions in the broadband signals. The distortions change significantly as the observation angle changes, moving further away from the main axis.

The another observation is that in the case of the matched reception, it is important to take into consideration the effect the channel has on appearance distortion and the signal detection. A comparison of the results of the reception with and without the channel influence being taken into account showed that detection is improved when the receiving filter is matched to the expected signal at the reception point rather than when matched to the transmitted signal. Knowledge of the channel transfer function, and following from that, of the type of the signal distortions improves detection of the signals transmitted in the presence of the noise.

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