PRELIMINARY INVESTIGATIONS ON IMPLEMENTATION OF TECHNOLOGY OF BROADBAND SIGNALS FOR MARINE BIOLOGY AND SEDIMENTS RECOGNITION

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This paper describes potential applications of broadband acoustic signals for marine biology and fisheries and acoustic precise profiling of the upper layer of sediments. Comparisons of the results of conducted experiments employing the same experimental setup but with different signals are presented. In each of experiments short pulses of CW signals and long pulses of up/down chirp signals were used. The basic theory of FM signals as well as some of the factors that must be considered when implementing this type of signal in actual systems are described.

INTRODUCTION

Almost all acoustic systems used for fisheries and biological oceanographic studies have to date used systems that transmit short CW tone pulses.

However, such animals as sea mammals or bats which use echolocation or birds which must communicate in noisy environment, use broadband chirp signals for this purpose. Complex, broadband signals have the number of virtues distinguishing them amongst different broadband systems [2,10].

Practical employments of acoustic systems using high frequency chirp signals to study the marine environment are relatively rare. Nevertheless, in literature we can find applications of the technique in military active sonar systems devices as early as in the 50s of XXth century.

In civil applications the first commercial devices called chirp-sonars which have been used for examinations of sea bottom deposits stratification [6,8], appeared at the turn of eighties and nineties. Advantages of linearly modulated signals were also utilized by divers in miniature devices for the underwater orientation. However, in the high frequency regime the explorations in this area are scarce. We should mention here that first although limited experiments concerning measurements of a bottom backscattering in the Baltic Sea with LM signals were taken more than ten years ago [5].

In the paper we compare the results of processed data for CW and LMF signals concerning the properties of the volume and bottom reverberations. The data discussed in this report were collected during experiments and trials performed for the grant and constitute a by-product of the main goal investigations.

1. MEASUREMENT SET

The setup used in presented experiments is comprehensively described and its parameters are introduced in the companion paper [4]. The functional block diagram of the setup is shown in Fig. 1. Depending on the type of surveying, the measurement set was used in two different variants with a variety of parameters such as different frequency, length of the CW signals and up or down chirp signals. In every presented experiment the transmitter and the receiver were mounted closely on a frame and functioning as a monostatic system. The CW and LMF signals were sent alternately.

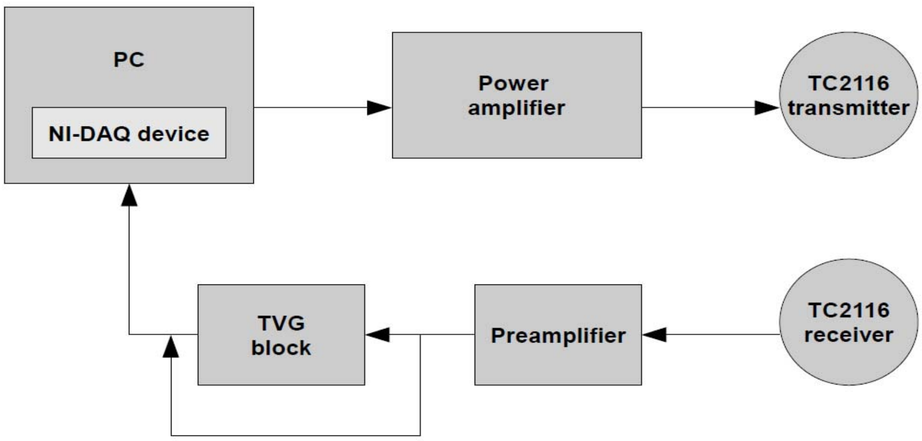

Fig.1. Functional block diagram of chirp echosounder

The experiments were carried out in two different environments :

- At sea (the Baltic Sea) – records were carried out both at the specified sites and during the movement of the vessel. Measurements were performed in areas with the sea depths of 20-80m. In the second variant, transducers inside a fairing were mounted along the ship board and towed at a depth of 1m below the sea surface. The time of emitted LMF pulses was set to 0.3-20 ms and was mainly dependent on the sea depth (distance to the sea bottom). The frequency was changing linearly in time from 40 kHz to 60 kHz or up to 80 kHz. Repetition of output signal was one ping per 0.3-4.0 second.
- In tanks – the aquariums in the Sea Fisheries Institute in Gdynia. The size of the smaller aquarium was about 1.4 x 2.0 x 1.0 m and the bigger one 2.0 x 3.0 x 1.0 m of height, length and width respectively. In the variant presented here, the frame with transducers was mounted in aquariums about 10 cm below the water surface. The transducers were directed vertically

downwards. During experiments inside of the aquariums, the time duration of the LMF output signal was set to 1 ms. The frequency was changing linearly in time from 40 kHz to 80 kHz. The CW signals were shorter – the pulse length was 0.3 ms. and the repetition of the output signal was from 1 to 3 pulses per second.

2. THEORETICAL BACKGROUND

The frequency of the tone-burst of the chirp signal is varying linearly within the pulse. The width of the frequency sweep is usually selected to be at least 25-50% of the center frequency of the chirp signal. The formula describing chirp signal is given by (1):

$$\begin{aligned} &u(t) = A(t)\exp(\omega_0 t \pm St^2/2 + \varphi_0) \quad for \quad 0 < t < T \\ &u(t) = 0 \quad for \quad t < 0 \quad and \quad t > T \end{aligned} \tag{1}$$

where $A(t)$ is the amplitude weight of a pulse, S is the sweep rate in units of hertz per second, ω_0 – angular frequency

It is generally preferred that the amplitude of the emitted signals should be constant over the whole sounding signal bandwidth. Since the frequency response and the transmitting sensitivity of the TC2116 transducers over the bandwidth of the slide signals in the application are varying, we performed the corrections of the sending and receiving signals. During emissions the amplitude of the weighted window was implemented online.

In the receiving mode the corrections were made during the postprocessing procedures. Prefiltering the received echoes through the digital filter with inverted frequency response characteristics of the transducer resulted in improved matched filtering.

The PC performs matched filtering of the received broadband signal, i.e. the real-time cross-correlation, to compress the reflected LFM signals in time to zero phase wavelets. When the bandwidth is sufficiently large, pulse compression provides better spatial resolution and improves the range resolution.

Mathematically, the compressed pulse (*CP*) is computed by taking the inverse Fourier transform of the convolution of the Fourier transform of the transmitted signal with the complex conjugate Fourier transform of the received signal.

$$CP = FFT^{-1}\left[FFT(P_{out}) * \left(FFT(P_{inp})*\right)\right] \tag{2}$$

CP – compressed pulse, FFT – Fast Fourier Transform, P_{out} – transmitted signal,
$P_{in\,p}$– echosignal, * Complex Conjugate

Amongst other advantages of applying this type of signals, we can mention progress in the assessment of object movement precision and theoretically high dynamics (to 80 dB) which significantly improves accuracy of the measurements.

3. LMF SIGNALS IN FISHERY AND MARINE BIOLOGY

In situ target strength measurement techniques require accurate measurement of the amplitude of single echoes. The quality of single echo amplitude measurements is affected by the ability to resolve echoes from individual targets from those of multiple scatterers or sea surface and bottom reverberations and the echo amplitude relative to the noise level.

Reverberation cannot be removed by any processing operation such as filtering, and the reverberation effects are the same for both CW and LFM systems with the same output pulse width. Among other advantages we could mention also that the FM sonars have low sidelobe levels – the ideal setup when we are obliged to perform a target location in the shallow water as lakes, rivers, seacoast waters, with the transducer(s) looking nearly horizontally.

The signal-to-noise ratio in a conventional echo sounder using tone-burst pulses can be improved by increasing the signal level or the pulse duration. In case of the CW pulses the signal-to noise ratio can be increased by transmitting a longer pulse, but this will reduce the spatial resolution and the ability to resolve presence of single scatterer at higher densities. Due to Heisenberg principle it is difficult to achieve both a good signal-to-noise ratio and good echo resolution using a conventional CW echo sounding system. SNR gain achieved in LMF systems is approximately equivalent to a pulse time (T)-bandwidth (B) product - BT.

The solution to this tradeoff between single echo resolution and signal-to-noise performance is to use a broadband type of signal different than conventional tone burst pulse. One of the possible types of signals is the FM signal which provides both good spatial resolution and good signal to-noise performance.

Finally it should be emphasized that the matched filtering keeps superposition of the backscattered energy from recognized targets. So, the total acoustic energy in the postprocessed signal is proportional to the average of energy per target and the number of targets in the ensonified volume. This detail is very important to introduce LMF sonars in the echointegrators [1]. This kind of systems are only developing in practice and the results of such experiments published in articles could be counted on the fingers of one hand [1,9]

4. EXAMPLES

The laboratory experiments which were undertaken for inspection of the viability of the new technique – measurements in the near field zone of TC2116 transducers were conducted in water tanks situated at the exhibition building of the Sea Fishery Institute in Gdynia. The acoustic climate inside of the tanks is very convenient for setup testing. High concentrations of bubbles and the electrical and acoustic noise from different surrounding mechanisms cause a lot of difficulties. Part of the experiment was conducted in aquariums with fishes. Beyond the acoustic tests the video recording was employed.

The short length of the sequences was required due to the fact that the tank was quite reverberant. The duration of pulses was 0.3 ms for CW signals and 3 ms for 40-80 kHz LFM signals.

Figures below show the images obtained with the two different techniques. Layered bottom which consists of very thin layers of grit, sand with some organic inclusions and finally the bottom glass wall is easily recognized during chirped soundings. Apart from, the fish presence detected by the chirp signals, there are some artifacts such as branches which constitute the scenery of experiment and are visible on the echogram. The CW echosounding gives only a blurred image, and fishes were not visible. It should be emphasize here that due to high range and azimuthally resolution, targets near bottom could be detected and recognized.

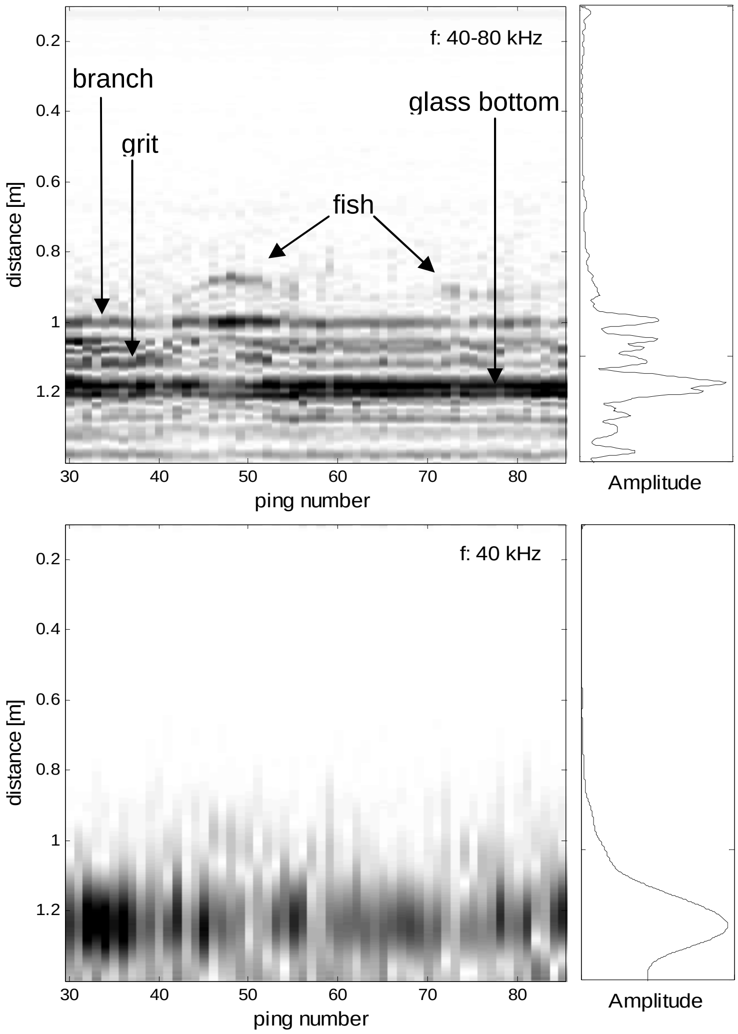

Fig.2. Echograms and averaged over 50 pings profiles showing the performance the equipment with the two signal types in the presence of fishes . The upper echogram is for a broadband for a processed LFM slide, at the bottom for the filtered tone-burst signal. Both signals have the same transmit power

Performed experiments proved usability of the chirp echosounder in a very shallow and noisy water environment.

Another investigation of the system behavior in strongly reverberating medium was planned at the deeper water of the Gdansk Gulf during the night fish migrations. The purpose of this experiment was to evaluate the possibility of the monitoring of targets movement in presence of fish. Dispersed fishes due to high scattering of ultrasound at their gas bladders constitute the strong background volume reverberation.

The example of time series of the reverberation in fish presence for both signal types are showed in Fig.3. Figure shows profiles of a CW echo and LFM signals after matched filtering versus depth, in the presence of dispersed fish. The parameters are for CW signal f=60 kHz, τ=0.3 ms, and for LFM f$\in$[40-80 kHz] and τ=10 ms. Sampling frequency of the echosignals was f_s=350 kHz. The signals were emitted alternately with the period of 1 s. The software was generating TVG function in the form: $TVG(r) = a * (ct/2)^2$, ('40 log(R)') which was applied to the returned signal. Both received signals were filtered digitally. The straight lines represent a threshold level, determined on the basis of the shape of histograms (Probability Density Function) where a) and b) are envelope of LMF echosignals and CW echosignals, respectively. Detected peaks are assumed to be echoes from single scatterers. Note that for both type of signals we could recognize single targets. In case of low density of fishes, the single and stronger echoes are better identifiable by the investigator. However, for the signal parameters used here we have distinguished 1.4 - 2 times more single scatterers with the LFM method as compared to the CW method.

Acoustic systems used in fish or plankton target strength measurement at medium and long ranges are often limited by the signal-to-noise ratio. Using of LFM signals, (or other complex signals) is simply a way to increase the signal-to-noise ratio when we do not have the option to increase an echosounder transmit power or to shorten the emitted acoustic pulse.

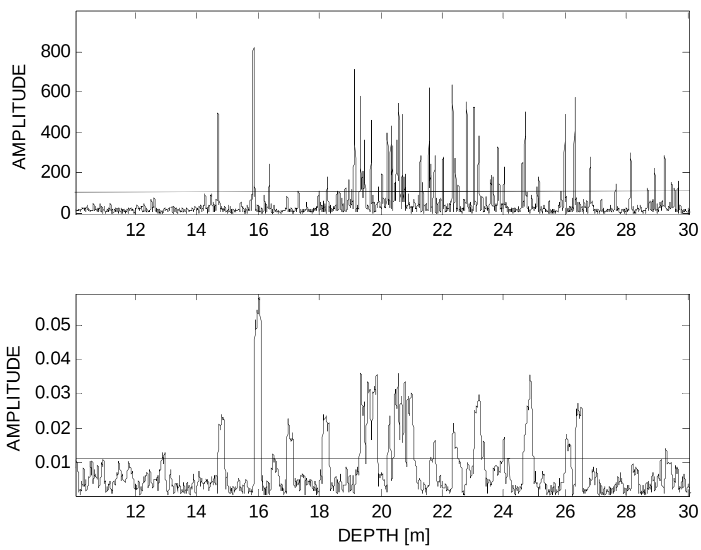

Fig.3. Profiles of the envelope of returned signals versus the range in presence of dispersed fish. The LFM signal after compressing in the upper part and for the CW pulses at the bottom. TVG function proportional to the r^2 – a distance form the transducers. The time span between pulses is 1 s

Theoretically, in case described in this paper, the up to 30 dB performance improvement (B=40kHz, T=30 ms) is equivalent to the 1000 increase in transmitted power or up to 14 increase in range detection, for the same transmitted power, comparing to CW pulse signal. However, we should keep in mind that the last estimation is realistic only for boundless environment.

We proved that the calibrated setup and almost simultaneous sounding with CW and LMF signals the sonar has the potential for fish quantitative abundance assessment with better detecting their presence, and better single target counting or echo integration.

However, the observations of diel migration obtained with the two presented methods are in agreement given quantitatively similar patterns.

We observe another problem that can happen with LFM systems such that a large target can produce smaller false targets. The appropriate applying of windows in time or frequency domain could improve the problem of more precise a target (fish) counting.

5. BROADBAND SIGNALS IN SEDIMENTS RECOGNITION

Chirp sub-bottom profilers have been extensively used during the last two decades. There are two advantages of this kind of systems. While using broad-band chirp sonar it is possible to estimate the attenuation of acoustical waves in sea sediments in real time. Another advantage is an exceptionally good depth resolution [6,8]. The remote sediment classification technique based on attenuation measurements from chirp sub-bottom profiler data was checked both at sea or in laboratory studies many times. Generally, with acceptable probability of sediments recognition, however due to the wide variance of results the errors are reasonably high.

At the ultrasonic frequencies somewhere above 30 kHz, different echo features are computed from echo envelopes, e.g. backscatter strength (at normal incidence), statistical skewness of the echo envelope, statistical time-spread [3], spectral skewness, spectral width, spectral kurtosis [12], Hausdorff fractal dimension [11] and many others.

By introducing the high-frequency chirp echosounder in acoustic characterization of seafloor sediments, we could effortlessly adjoin new class of parameters. Spectral characteristics of the backscattered signal are related through the acoustic attenuation on the sediments category. Tested high-frequency chirp echosounder, in contrast to the mentioned commercial seismic chirp profilers has finer depth resolution, but inevitable loss of the penetration depth.

6. CHIRP ECHOSIGNALS FROM SEDIMENTS

During surveys in the PEZ with the high-frequency single-beam broadband system, a database of echoes was collected. Postprocessing of the bottom backscattered signals in relatively wide range of frequencies allows to extract new characteristic features of the returned signal - more than simple echo envelope features. It enables us to enrich our knowledge about sediments distribution.

As an example, some spectral moments and some of their combinations could be useful for a description of properties of signals returned from different sediment layers (stratigrafic units). The moments of spectra are defined as [7]:

$$m_r = \int_o^{\infty} \omega^r S(\omega \mid t) d\omega \approx \int_{\omega_1}^{\omega_2} \omega^r S(\omega \mid t) d\omega$$; for r=0,1,2, ... , where $S(\omega|t)$ – instantaneous signal spectrum. $\omega=2\pi f$; t – time.

The first spectral moment (central frequency–m_1) and bandwidth factor $Q(t) = \sqrt{1 - \frac{m_1^2}{m_0 m_2}}$ for chirp signals returned from the bottom showed in Fig. 4. are presented if Fig. 5

Comparing the echograms we observe that apart from common features, the echosignal envelopes display some dissimilarities. The main noticeable difference between them is the thin, approximately 20cm thick, acoustically soft layer, displayed in the chirp echogram, not recognised by the 60kHz CW signal. Also other statistical parameters of the both signals are quite different. One of them, the fractal dimension D for the bottom backscattered signals envelopes for the compressed chirp and CW signals are shown in Fig. 6. We have applied the approach based on the Hausdorff-Besicovitch fractal dimension estimation from the slope of the log-log plot of the semivariogram of the echo envelope.

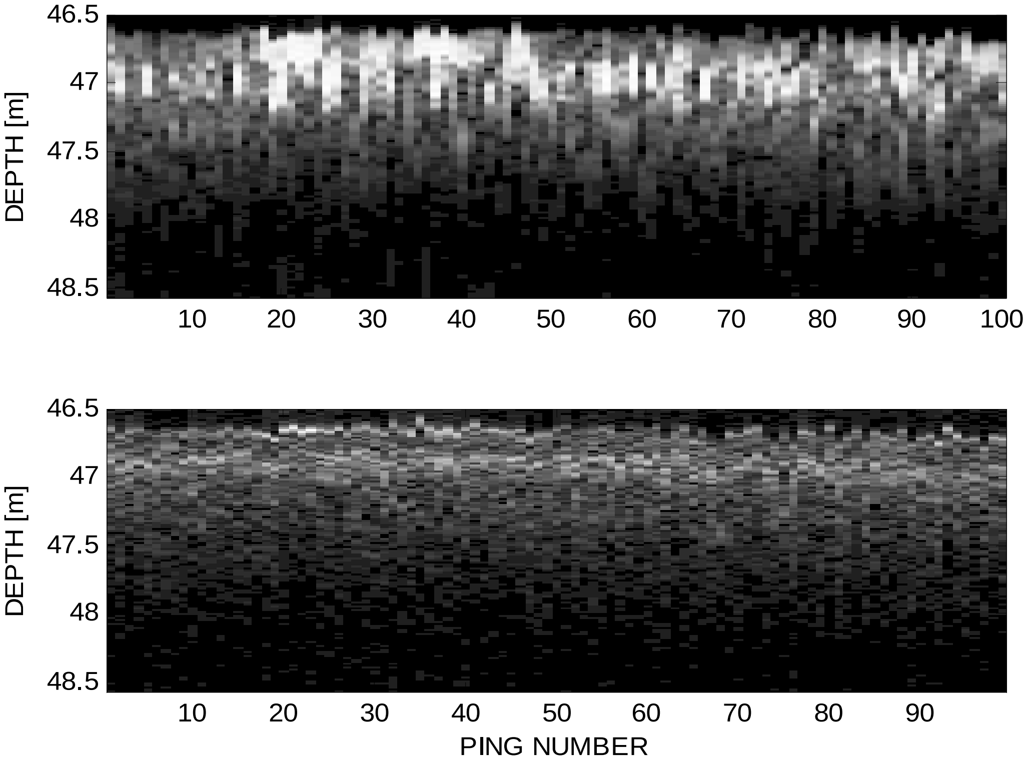

Fig.4. Comparison of echo from sandy bottom covered with thin layer of fluffy sediments. At the top CW at 60 kHz backscattered signals, with duration T=0.3ms. At the bottom with broadband signal in frequency interval 40-80 kHz and duration of signal T=10ms. Data collected from anchored ship Oceania at the site with coordinates

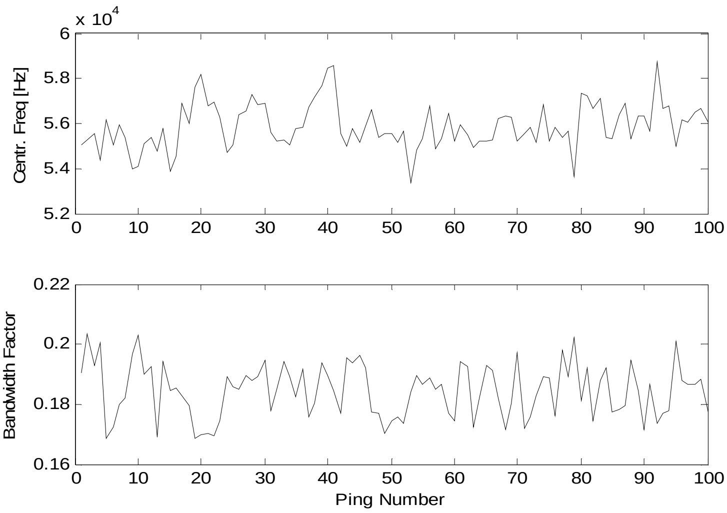

Fig.5. The central frequency and bandwidth factor of the raw chirp echosignals presented in the echogram in Fig.4

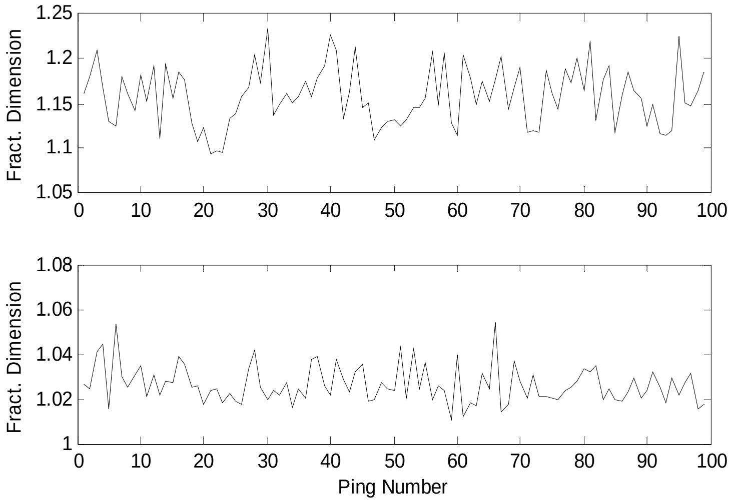

Fig.6. Fractal dimension estimated using the semivariance technique for the envelopes of the bottom backscattered signals, for the compressed chirp signal at the top, and for CW echosignals at the bottom

The difference in the fractal dimension of time series are clearly visible. The higher values of the fractal dimension for chirp signals are due primarily to the more spiky compressed broadband signals. It is worthy to point out that higher dynamics of fractal dimension of the LMF echoes gives more contrasted data sets for different types of sediments.

The examples of the mean frequency response for LMF signal backscattered from different type of sea bottom are shown in Fig. 7. We present a gassy marine clayey silt sediment, where signal was penetrating a thin bottom layer (with thickness about 1 m) and silty clay where penetration by the signal was significantly larger (about 8 m) and where layering of sediments was clearly visible in the chirp signal after matched filtering.

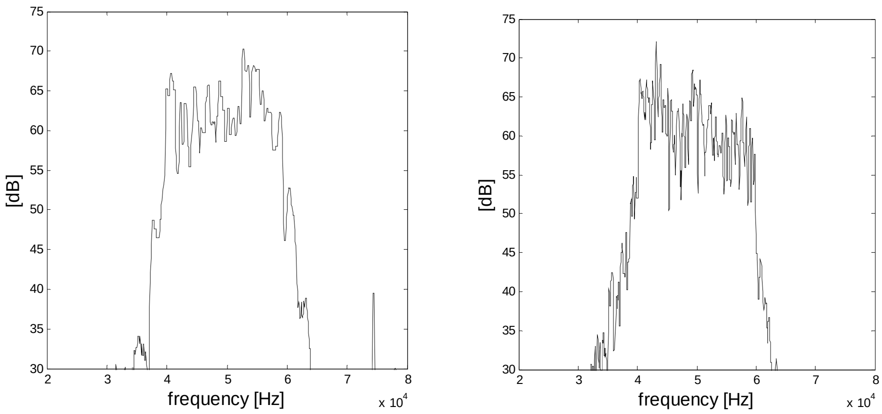

Fig.7. Mean frequency response of bottom signals from a) marine clayey silt gassy sediments and b) silty clay

7. SUMMARY

The comparisons between CW pulses and LMF signals volume and bottom reverberations were conducted employing the same experimental setup. The evaluation shows that the LMF technique greatly reduces the noise contamination of the signals, making it possible to work with lower power and without many pings averaging for target detection.

The first results of the implementation of LMF for peculiar purposes show that this kind of signals is very appealing for biological underwater measurements, due to its high immunity to the additive noise and to the exceptionally easy and fast processing. The software implementation required for the deconvolution of the impulse responses even on a notebook PC, resulted in a powerful, and yet low-cost portable hydroacoustic system.

Also employment of high-frequency LMF signals in sediments classification purposes and surveillance of a fine sea bottom stratification soft sediments in case of gives encouraging results.

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