APPLICATION OF MAXIMUM-LENGTH SEQUENCES TO IMPULSE RESPONSE MEASUREMENT OF HYDROACOUSTIC COMMUNICATIONS SYSTEMS

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There is a growing interest in digital transmission of telemetry data on ultrasonic waves. The dependence of signal attenuation on squared frequency, specific to the hydroacoustic systems, induces problems that do not exist in monochromatic, narrowband radio communications systems. For adapting the transmission parameters to current propagation conditions, a precise knowledge of instantaneous changes of channel performances is needed. Simulating and testing of broadband communications techniques require robust, reliable and efficient method of impulse response measurements in natural exploitation conditions. The paper presents the MLS (Maximum-Length Sequence) correlation method applied to impulse response measurements of electroacoustic transducers as elements of communication chain.

INTRODUCTION

There is a growing interest in digital transmission of telemetry data on ultrasonic waves, revealed by the underwater acoustic professional community. Underwater acoustic links support fixed oceanographic instrumentation as well as autonomous research and military vehicles. Bandwidth-efficient communications systems are of spreading use in single-user links as well as in multi-user networks of underwater sensors. Modern acoustic modems realize high-speed data upload from remote instruments. Depending on underwater channel, available transmission rates vary from 100 bps in shallow water long-range applications to 30 kbps in deep-water short-range data transmission [1].

The acoustic communications systems make use of modern fixed and mobile telecommunications solutions, including dynamic adaptation of modem parameters to current quality of the transmission channel. Signal transmission standards implemented in the system, i.e. channel-coding technique and modulation scheme, strongly influences overall features of the communications system in a given channel. These standards define broadly meant protocol that is a “soft” component of any communications system [2].

Underwater acoustic communications systems work in very low frequency band and are broadband in direct sense. The dependence of signal attenuation on squared frequency, specific to the hydroacoustic systems, induces problems that do not exist in monochromatic, narrowband radio communications systems. The effective transfer function changes much with the distance – the effect unknown in radio systems. So the quality of the ultrasound transmission depends not only on the underwater channel-induced disturbances, but also on the transmitter-receiver distance. For adapting the transmission parameters to current propagation conditions, a precise knowledge of instantaneous changes of channel performances is needed. Hence the growing need of efficient impulse response measurements, working effectively in natural conditions of systems exploitation. Correlation measurement methods are the best for such applications.

1. DIRECT AND CORRELATION METHODS OF IMPULSE RESPONSE MEASUREMENTS

The idea of *direct measurements* of the impulse response bases on exciting the tested system with a short pulse having flat spectrum in the whole frequency band of the system transfer function. Such a pulse can be treated as technical realization of Dirac’s delta function.

However, the pulses generated by electroacoustic measurement equipment have low energy, sufficient mere in laboratory conditions – in small rooms and test tanks. In big auditoria and natural reservoirs signals received at the system output are of very low signal-to-noise ratio (SNR). It can be ameliorated by multiple repetitions of the test and averaging results of consequent measurements.

In practice, sparkers, starting pistols, air guns and explosives are used for generating high amplitude pulses directly in the propagation medium. Although they approximate satisfactory the ideal Dirac pulse, they are difficult to synchronize – first, when repetition is needed, and second, for synchronized reception. Moreover, nonlinear effects accompanying such a way of creating acoustic energy, introduce errors, especially in the vicinity of the pulse source. When thinking of communications systems, these methods exclude transmitters as system elements and are limited to characterizing mere the channel (or the channel-receiver cascade).

The *correlation methods* of measuring the impulse response make use of special features of broadband signals having narrow, impulse-like autocorrelation function. The condition is the same as for the short pulses: spectral density of the test signal should be constant in the whole frequency band of the system transfer function. White Gaussian noise (WGN), pseudo random “noise” binary functions (PRN) and chirp signals (sinusoids with linear or logarithmic frequency sweep) are practical signals having Dirac’s impulse-like autocorrelation.

It can be easily shown that when such a signal is put into the system and the output signal is crosscorrelated with the input one, the calculated crosscorelation function is a good approximation of the tested system impulse response.

The WGN and chirp analog-generated signals are often used in direct measurements of power transfer function of linear systems. However, they are not suited to correlation measurements of the impulse responses as their waveforms are difficult to be precisely reconstructed at the receiver. Moreover, in the case of the WGN as testing signal, external noise limits the precision of results, as it is impossible to distinguish at the output between the test-generated noise and the intruding one.

Digitally generated signals are the best for the correlation methods as their waveforms are perfectly known and are easy to be reconstructed throughout the whole measurement procedure. The most popular are digital chirp signals and binary bipolar signals. The latter are generated on the base of the pseudo-random m-sequences, known as Maximum Length Sequences (MLS) [3].

In communications systems working in pseudo continuous-wave mode, the limit of the transmitting amplitude is the same for special signals as for a single pulse. For a broadband test signal L times longer than the single pulse, its energy is L times higher and the correlation measurements give the SNR L times higher than the direct pulse ones. It is worth saying that the MLS technique gives SNR 3dB higher than the corresponding digital-chirp method.

The MLS technique is one of the basic room acoustics measurement methods recommended by ISO standards [4].

2. BASICS OF CORRELATION METHOD

In *a linear time-invariant system*, the output signal $y(t)$ has the form of convolution integral of the input signal $x(t)$ and the system impulse response $h(t)$:

$$y(t) = x(t) * h(t) = \int x(\tau)h(t-\tau)d\tau \tag{1.1}$$

The correlation function $\rho_{xy}(t)$ of the output and input signals is expressed as:

$$\rho_{xy}(t) = \int x(\tau)y(\tau - t)d\tau \tag{1.2}$$

Substituting Eq. (1.1) into (1.2) yields:

$$\begin{aligned}\rho_{xy}(t) &= \int x(\tau)\int x(\tau)h(\tau-t)d\tau d\tau = \int h(\tau)\int x(\tau)x(\tau-t)d\tau d\tau \\ &= \int h(\tau)\rho_{xx}(\tau-t)d\tau = h(t) * \rho_{xx}(t)\end{aligned} \tag{1.3}$$

When the autocorrelation function of the input signal approximates the Dirac delta distribution, the crosscorrelation of the output and input signals approximates the system impulse response:

$$\rho_{xy}(t) \approx h(t) \tag{1.4}$$

In *a discrete time domain linear system*, the output signal $y[n]$ has the form of the following discrete convolution sum of the input signal $x[n]$ and the system impulse response $h[n]$:

$$y[n] = x[n] * h[n] = \sum_{m=0}^{L-1} x[m]h[n-m] \tag{2.1}$$

The correlation function $\rho_{xy}[n]$ of the two signals is expressed as:

$$\rho_{xy}[n] = \frac{1}{L}\sum_{m=0}^{L-1} x[m]y[m-n] \tag{2.2}$$

Substituting Eq. (2.1) into (2.2) yields:

$$\begin{aligned}\rho_{xy}[n] &= \frac{1}{L+1}\sum_{m=0}^{L-1} x[m]\sum_{k=0}^{L-1} h[m]x[m-n-k] = \\ &= \frac{1}{L+1}\sum_{k=0}^{L-1} h[k]\sum_{m=0}^{L-1} x[m]x[m-n-k] = \sum_{k=0}^{L-1} h[k]\rho_{xx}[n-k] = h[n] * \rho_{xx}[n]\end{aligned} \tag{2.3}$$

that is the input signal autocorrelation function convolved with the system impulse response.

3. MAXIMUM LENGTH SEQUENCES AND THEIR PROPERTIES

MLS is a binary sequence generated by N-stage LFSR (Linear Feedback Shift Register) working either in the Galois configuration or the Fibonacci one (Fig. 1) [5].

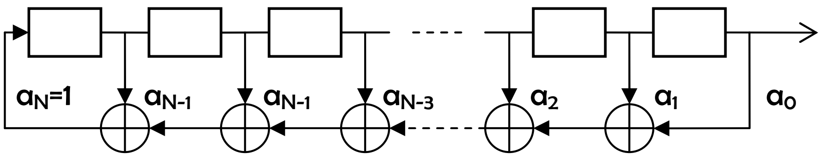


Fig.1 Shift register –Fibonacci configuration

The register cells hold mere binary values: 0 or 1. The cells outputs are connected by XOR gates. A periodic sequence of binary samples is generated at the output of the shift register.

The generation polynomial $G(X)$ describing combination of the register unpins has the following form:

$$G(X) = X^N + a_{N-1}X^{N-1} + a_{N-2}X^{N-2} + \ldots + a_2X^2 + a_1X + 1 \tag{3.1}$$

where: $a_{1\ldots N-1}$ − 0 or 1 weight of corresponding register unpin,

$X^{0\ldots N}$ − 0 or 1 value of register cell.

The length of the sequence period depends on the values of the a_N factors and does not depend on initial binary word in the register (the latter affects only the initial phase of the generated sequence). The maximum length L of the recurrent period generated by a N cell register is:

$$L = 2^N - 1 \tag{3.2}$$

The sequence which the length *L* is given by Eq. (3.2) is called Maximum Lengths Sequence (MLS). For each *N* there is at least one combination of register unpins that gives a MLS. All other combinations give shorter period.

The polynomials describing MLS are primary ones and can not be reduced to a product of lower order polynomials. The MLSs have two interesting features deciding on its broad technical implementation, *ex.* in radar pulse compression technique, spread spectrum communications and architectural acoustics measurements [2]:

Equilibrium property –the number of zeros and ones in one sequence period is almost equal (the difference equals one)

Correlation property – the values of autocorrelation function of maximum length sequence with symbols ±1 are -1 for arguments different then zero and $2^N - 1$ for zero argument.

The autocorrelation function for pseudo-random MLS binary signal has a form that is not distant from a perfect impulse:

$$\rho_{xx}[n] = \delta[n] - \frac{1}{L+1} \tag{3.3}$$

where: $\delta[n]$ − the Kronecker delta,

Substitution of Eq. (3.3) to Eq. (2.3) gives:

$$\rho_{xy}[n] = h[n] - \frac{1}{L+1}\sum_{k=0}^{L-1} h[k] \tag{3.4}$$

The second and third components in Eq. (3.4) represent a DC average value of the impulse response. It can be neglected in most of the systems that do not transmit constant value, including electroacoustic transducers, and dropped off. In effect, we obtain:

$$\rho_{xy}[n] \approx h[n] \tag{3.5}$$

It means that when a MLS sequence is used as the input signal, the crosscorrelation function of the input and output signals approximates the system impulse response. As the digital signals and calculations are periodic, the result is periodic as well, being called Periodic Impulse Response (PIR) (Fig.6).

The correlation property is fundamental for the practical use of MLS in the impulse response measurements. The normalized non-zero values of the autocorrelation function decrease with the length L of the MLS. The autocorrelation function of MLS is very close to theoretical Dirac's impulse. Fig 3 presents such a function for N=3 (L =7).

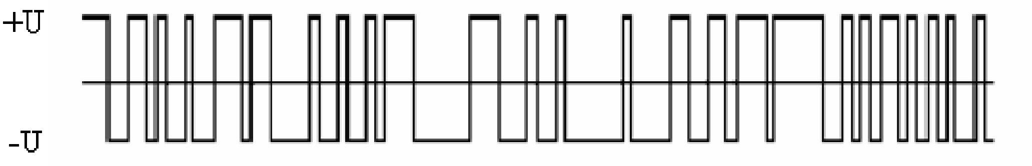


Fig.2 MLS bipolar test signal

Each combination of register unpins has a mirror reflection sequence. For example, for N=16 order of the sequence length $L=2^{16}-1=6555$ there are 26 combinations of 4 register unpins, 184 combinations of 6 unpins, 406 combinations of 8 unpins, 324 combinations of 10 unpins, 78 combinations of 12 unpins, and 6 combinations of 14 unpins [5]. When *N* grows up, the number of possible MLS sequences increases very fast.

When the MLS signal is generated for measurement applications, +U and –U voltage values are prescribed to the logical zeros and ones (or reverse) at the register output (Fig. 2).

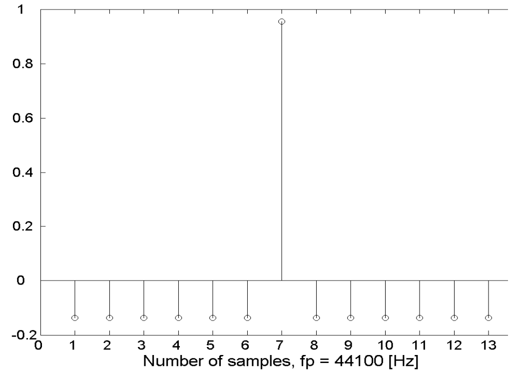


Fig.3 Autocorrelation function of MLS (*N*=3, *L*=7)

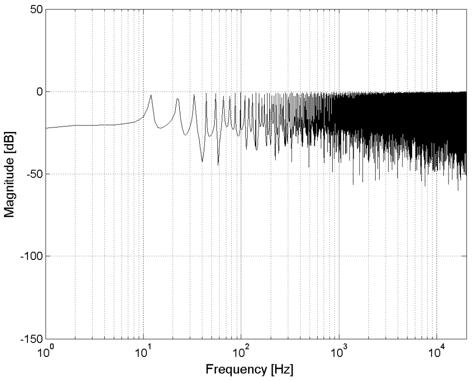


Fig.4 Power spectrum density of MLS (*N*=12, 16 MLS periods)

The power spectrum density of MLS is constant *for all the discrete frequencies* in the covered frequency band, except for the DC offset, and equals $1+1/L$ (Fig.4). So the average power spectrum density of MLS is 2^N times greater then that of a single test pulse. The MLS autocorrelation function has small negative DC offset that equals $-(1+L)^{-1}$. Such a DC component does not exist in white noise test signals. However, the offset is negligible as it is 2^N times smaller than the maximum value (*ex.* for N =16, the offset level is -96dB).

4. MLS BASED MEASUREMENT SYSTEM

The impulse response measurements have been performed by the authors of underwater acoustic loudspeaker and ultrasonic transducers, in the configuration presented in Fig. 5. The amplified periodic MLS sequence from PC audio card was put into the measured transducer. The signal received from the hydrophone was amplified, A/D converted and put into the correlator. The crosscorrelation function of the input MLS sequence and the received signal was calculated with the use of the Fast Hadamard Transform algorithm (FHT) [4].

The time-domain sequence at the correlator output represents the impulse response of the linear system consisting of the measured electroacoustic transducer, propagation medium (measurement tank) and receiving transducer (hydrophone). This sequence is then Fourier-transformed into the frequency domain, expressing the measured system transfer function.

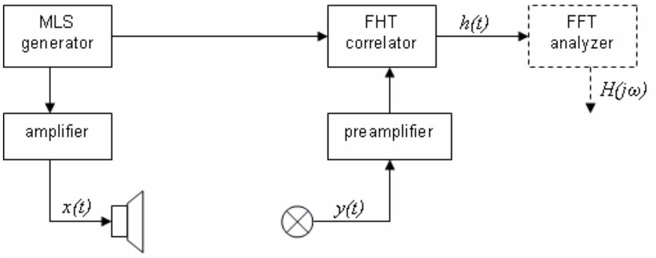


Fig.5 Measurement system configuration

For obtaining the desired impulse response, the MLS should be repeated at least twice. It comes from the fact that the MLS-involved correlation functions reach the expected form beginning from the second period, after a transient lasting the whole first MLS period. The crosscorelation function represents the periodic impulse response (PIR) starting from the second emission of the MLS. Similarly, after turning off the MLS signal, the calculated crosscorelation differs from the PIR. In practice, it is reasonable to repeat the MLS at least three times to have at least two PIR signals as a visual verification of periodic calculation correctness (Fig.6).

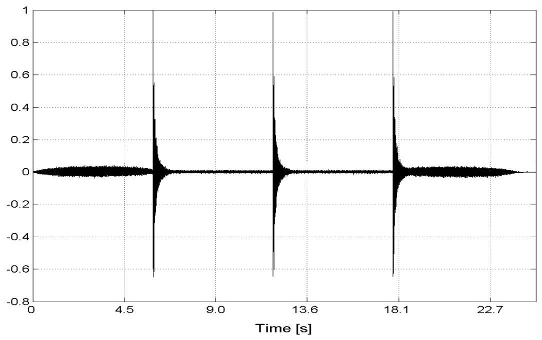


Fig.6 Periodic impulse response (N=18, three MLS periods, two PIRs)

It is obvious that the period of the MLS signal should be not shorter than the overall length of the measured impulse response of the system, including possible multipaths and reflections.

The MLS correlation techniques give results with high SNR. However, one should be aware that the sampling frequencies of the emitting sequence D/A converter and the received signal A/D one, must be the same.

The above means the requirement of a perfect synchronization of the communications system receiver with the transmitter. In measurement systems, it is advised to use the same hardware in both *in situ* measurements and post-processing calculations.

5. MLS AND DIRECT IMPULSE RESPONSE MEASUREMENT RESULTS

The impulse responses (PIRs) and corresponding transfer functions measured with the MLS arrangement described in the previous section, are presented in Figures 7 - 9.

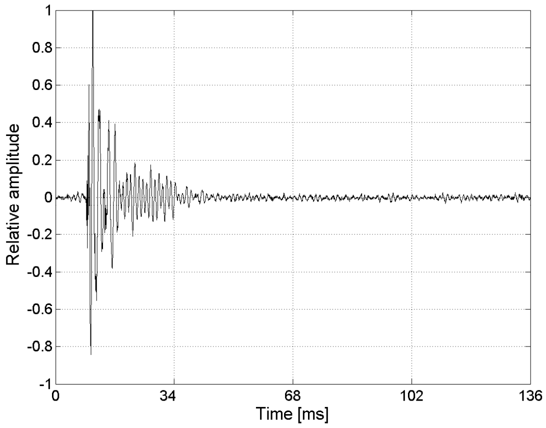


Fig.7 PIR of underwater loudspeaker measured in reverberant tank (MLS, N=15)

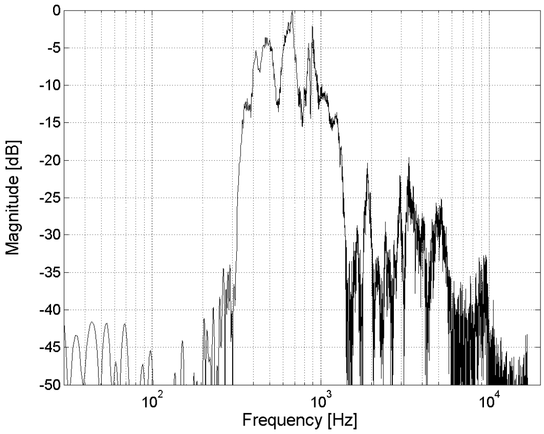
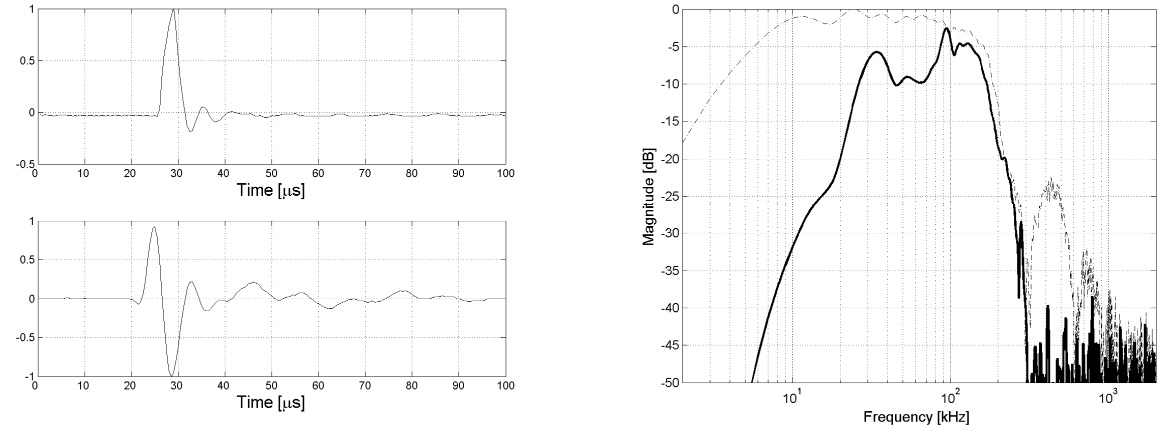


Fig.8 Frequency spectrum of the PIR of Fig. 7

Transmission characteristics of an underwater band-pass (350 Hz - 1.2 kHz) loudspeaker have been measured in the measurement tank with hydrophone placed 1.5 m apart. A MLS sequence of N=15 has been used (L=32767). Fig. 7 presents *initial part of* the loudspeaker impulse response. Because of low frequencies, the measurement tank wall reflections could not be separated and have influenced the corresponding transfer function (Fig. 8).

Fig. 9 shows results of direct impulse response measurements of a multi-resonant ultrasonic transducer. The transducer was fed with short exciting pulse (a) and the system response (b) was measured directly with a hydrophone. Since the input pulse has a relatively flat spectrum in broad frequency band, the received signal can be seen as approximating well the impulse response of the transducer-hydrophone system.



a)

b)

Fig.9 Measurement results of ultrasonic transducer in test tank: a) input (top) and output (bottom) pulses, b) amplitude spectrum of input test pulse (-----) and output pulse (__)

Taking into account the classic, narrow-band resonance approach, the above transducer can be used either in the frequency band of 35 kHz or, better, 90 kHz. However, modulation techniques used in broadband communications systems are able to make use of every frequency band in which the SNR exceeds 20 dB. Hence, the useful frequency band broadens much, especially for short and medium ranges.

The measurements as described above, made with short pulses, give good results in laboratory conditions. However, the communication performances of ultrasonic systems should be tested in natural working conditions. The MLS method of on-line measurement of impulse responses and instantaneous transfer functions is better suited to the latter application.

6. CONCLUSIONS

The MLS measurements presented in the paper were performed with the use of standard air-acoustic measurement hardware and has been limited to 20 kHz, the sampling frequency being 44,1 kHz. For full-scale hydroacoustic measurements covering the frequency band of, let say, 200 kHz, high speed D/A and A/D converters are necessary, with sampling rate of the order of 500 kilosamples per second.

An MLS measurement system working in wide frequency spectrum up to 200 kHz is being under construction in the Department of Marine Electronic Systems, Gdansk University of Technology. It will make possible to study *in situ* the influence of the underwater acoustic channel on the performances of broadband data transmission links.

The MLS techniques broadly used in architectural acoustics, spread spectrum communications and radar pulse compression technique [6], will surely find their place in underwater acoustics. The hydroacoustic applications of the MLS signals published up till now, in reservoir bottom profile sounding [7] and zooplankton sonar survey [8], seem very promising.

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