UDK: 681.883
COSATI: 20-01

Spectral characterization of the hydroacoustic field of the vessel in the river environment

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Acoustic noise generated by vessel motion in the test range on a river is the subject of this paper. The hydroacoustic field of the vessel is analyzed using different methods. The analysis was performed in time and frequency domain. The acoustic signals are analyzed using classical concept of the spectral analysis, parametric models of random processes and bispectrum analysis. Particular interest was dedicated to identifying narrow band contributions to the total spectrum of the ship hydro-acoustic noise.

Key words: **hydroacoustics, hydroacoustic field, hydroacoustic noise, ship, river, hydroacoustic signal, signal spectrum, bispectrum, signal identification.**

Introduction

HYDROACOUSIC field of the vessels has over a long period of time been an important subject in the research and development of Navies worldwide. Today, after more than a hundred years of research and development and its application in various naval combat systems, this assertion is still valid. Hydroacoustics is a branch of technical sciences which incorporates many disciplines, such as acoustics, signal analysis, physics, electronics, sensors, and etc. widely used in planning and realization of numerous military systems, as well as non-military applications. Namely, the results of theoretical and practical investigations conducted in the last six decades are being used in:

- systems for underwater inspection;
- underwater communication;
- navigation;
- underwater telemetry;
- underwater combat systems;
- investigation of the biosphere using acoustics methods, and
- investigation of natural resources of the seas and oceans [1].

The use of military hydroacoustic devices is common in various types of naval systems such as: war ships, submarines, naval helicopters, diving equipment, torpedo and naval mine systems, equipment for detecting and locating objects in the water environment, underwater communication equipment, etc.

Underwater signatures denote all fields (e.g. acoustic, electro-magnetic or pressure) revealing the presence and characterizing naval vessels by underwater sensors. Weapons, like sea mines and torpedoes, use these sensors to detect, classify and localize their targets. To deal with this threat, underwater signature control of the vessels is the key element of naval platform design and operation. Reliable signature prediction models are essential throughout the life cycle of the naval platforms, ranging from preliminary concept studies, detailed design studies, signature control and operational guidance to counseling at the final disposal of the platform. The improved capabilities of detecting sensors and signal processing as well as advances in platform and propulsion system design, require continuous development and improvement of the prediction models in the field of vessel signature.

Vessel acoustic signatures are most important when naval military operations are conducted. Noise ranging is performed after major maintenance work, modifications or installation of the new equipment, in order to reveal any changes in the radiated noise levels of the vessel. Noise levels of the new vessels are measured to ensure that the radiated noise is within the limits stipulated by the project specifications, and that noise levels are in accordance with other regulations and requirements. It is customary that both the static and dynamic ranging of the vessels is carried out in practice.

Static ranging is carried out when the vessel is anchored in the static range. While performing the static tests, various units that are on-board the vessel (pumps, funs, blowers, generators, air conditioning, etc.) are started or turned on, and the noise they produce is measured.

Dynamic ranging is carried out by means of vessel following a particular course. The noise from the vessel is then analyzed when it passes specific points on the course. The most interesting point is the Closest Point of Approach, or (CPA) point. Normally, the vessel is tested by performing a number of test runs. Acoustic noise ranges have always been situated where, besides a low ambient noise level, the water is relatively deep, and the sound velocity profile is isovelocity.

Ships and submarines range from 30 to 300m or more, during propelling through the water and deliver from a few thousand to a hundred thousand shaft horsepower, while a

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small portion of this tremendous energy is radiated from the vessel into the water environment as acoustic energy [2].

Detecting the presence of the vessels in the water is possible either by directly sensing acoustic energy radiated from the object, or by transmitting an acoustic signal and detecting the reflection (echo) from the object. Systems that work on target-generated acoustic signals are called passive, while systems relying on echo detection are active systems.

In addition, acoustic source-level measurements were done for a variety of merchant ships. Scrimger and Heitmeyer presented in their report a set of 50 source spectra obtained from merchant ships near Genoa, Italy [3]. The radiated noise was measured over a 6 day period using a horizontal hydrophone array.

Knowing the parameters of hydroacoustic signals radiated from vessels is of particular importance when the goal is detection, identification and localization of the vessel. Namely, the information about vessel characteristics is contained in the signal of the radiated acoustic noise. The main contribution to the radiated acoustic noise of the vessel in the water environment is given by:

1. Propulsion system, which includes the engine, reduction gears (if any), drive shaft, bearings etc.
2. Propeller which, although a part of the propulsion system, contributes to the generation of the acoustic signals in a quite different way. Namely, the noise is a consequence of cavitations produced by the rotating blades.
3. Auxiliary machinery, such as non-propulsion related mechanical and electrical systems (air conditioning, electrical generators and pumps).
4. Hydrodynamic phenomenon i.e. radiated flow noise and flow-induced excitation of plates or other structural features of the hull.

The main contribution to the process of noise generation is given by the propulsion system of the vessel, which generates power-full rotation motion of the drive shaft, gear leaver and other ship systems. Slight dynamic unbalances of these devices result in oscillating forces appearing. Frequency of the drive shaft rotation and fundamental rotation motion is transformed into higher or lower vibrating frequencies during the process of the vibration transfer through the ship’s hull structure. The study of propagation of elastic waves in the ship bulk structure is a special scientific discipline. According to the theory of dynamic elasticity, solids can transmit not only longitudinal waves like fluid do, but also flexural, shear and torsion waves as well as their combinations. The process of wave propagation is actually a process of energy propagation. The researchers Goyder and White were the first to introduce the concept of vibrating power flow in 1980 [4]. They developed the numerical models of power flow in basic beam and plate structures using mobility method. Vibrating energy in the near field is mainly transmitted by beams, and when distance to the excitation grows, the energy is gradually radiated to the plates in beams; so in the far field, energy is mostly in plates. Deck plating is the last plate where the vibration energy passes into elastic water environment. Such elastic disturbances of water are commonly designated as underwater radiated noise of the ships.

The spectrum of the radiated acoustic noise of the vessels possesses some special features. Namely, the spectrum contains a broad continuous spectral components as well as narrowband or/and sinusoidal components. Such characteristics of the spectrum, depending of their origin, may or may not be functions of speed, depth, or other factors related to the operation of the vessel.

Underwater noise is recorded using special sensors, called hydrophones. Hydrophones are pressure sensors capable of converting small fluctuations of pressure from the water environment into analog electrical signals whose voltage amplitude is proportional to the intensity of the water pressure at the place of the hydrophone. The acoustic signature is usually measured at a relatively close range, such as 100 or 200 meters, and converted to the reference range of 1 m using the spherical spreading low, if recording of the radiated noise is done in deep water environment. If the measurements are performed in medium or shallow water environments, then another law of spreading of the acoustic waves should be used, cylindrical or a combination of spherical and cylindrical spreading. Relatively close range is choosen because the seawater possesses filtrating properties and therefore higher frequencies are attenuated, since the absorption coefficient increases with frequency.

Estimation of the parameters of electrical signals obtained when recording a passing ship's characteristics is an important task when the primary goal is the problem of the ship identification. In addition, radiated acoustic noise possesses information about ship characteristics. As pointed out previously, the most important contribution to the noise characteristics gives the ship propulsion system which generates the power of rotating motions.

Spectrum analysis enables acquiring insight into the distribution of acoustic energy in the frequency domain. Discrete Fourier Transform (DFT) provides a link between time and frequency content of the signal. But such analysis can not give a direct answer to the question whether any kind of connection between local maximums in the observed spectra exists. Therefore, it is necessary to perform addition analysis. One direction in the investigation would be to observe the phase coupling in the complex acoustic signal, using a standard procedure, the so-called higher order spectral analysis. Higher order analysis was used for the first time in the second half of the last century emerging as a need for solving the problem of recognition radar signals reflected from multiple obstacles.

The measuring systems in the field of hydro acoustic detection of vessels are possible to divide in two groups, the one channel, and multi channel measuring systems. The simpler, one channel detection system enables measuring hydro-acoustic field of the vessel in an area of the water environment. Multi-channel system enables measuring space distribution of the hydro-acoustic field of the vessel. Hydro-acoustic field of the vessel is not uniformly distributed in the water environment. Therefore, multi-channel systems deliver a better insight into the phenomenon of the vessel hydro-acoustic field. The data that were acquired using one measuring channel and serves as illustration of the characteristics of the vessel’s hydroacoustic field are presented in this work.

An example of the modern acoustic range

The measuring of the radiated hydroacoustic field of the vessels is performed in special test ranges which are equipped with complex measuring and other equipment. As an example of the modern acoustic test range is the acoustic range at Heggernes, near Bergen, Norway, which is used for measuring noise from all types of NATO naval vessels, and some civilian ships, too [5]. The structure of the acoustic test range is shown in Fig.1. It is possible to do both the static and dynamic ranging of vessels at such test range.

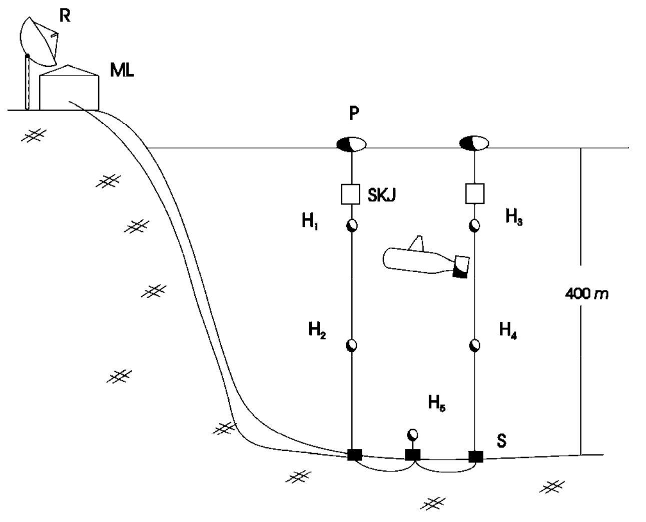

Figure 1. Scheme of the modern test range. ML – measuring laboratory, R – radar, H_1, …, H_5 hydrophones, SKJ – communication unit, P – buoy [5].

The depth of the acoustic range is about 400 m and the bottom is muddy, so unwanted reflections are minimized. Five hydrophones (H_1,…H_5) are placed in the vertical plane, which is normal to the course of the vessel. The upper pair of hydrophones is set to a depth of about 20m below the surface, while the lower hydrophones are at the depth of about 90m. In case of static testing, underwater telephone line for voice communication with the vessel tested is available and it is designated with (SKJ) in Fig.1. The hydrophones are connected with measuring equipment, placed at the measuring laboratory (ML), by long signal cables (about 2km). Monitoring position and speed of the surface vessels is performed by radar, which is marked by R. The signal to noise ratio decreases if the hydrophones are too far away from the noise source, and background noise must be at least 6dB bellow the source.

Laboratory of the test range is equipped with a wide variety of measuring equipment including PULSE multi-analyzers of the Brüel & Kjær and hydrophones of the same producer. The computer that integrates all components of the measuring equipment has hard disk racks that enable users to ensure that their ship noise data will be secret and unknown to other users.

The acoustic test range at Heggernes equally uses Royal Danish, Royal Norwegian, Dutch and German navies, but the Material Command of The Royal Norwegian Navy has an overall responsibility for the operation and maintenance of the acoustic range.

The characteristics of the radiated ship noise in the river test range

The measurement of the radiated HA noise of the ship is done in the river environment – the river test range. The ship was moving along the course which overlapped with river stream, with constant velocity of about 9 knots. Position of the ship during noise measuring is presented in Fig.2. The hydrophone of the B&K 8104 type was dipped at the river bottom at a depth of about 10m, Fig.3. The depth of the river test range was at the level of about 10m without significant fluctuations.

The electrical signal from the hydrophone is amplified by the B&K 2635 conditioning amplifier and then recorded using B&K 7004 type recorder. The measuring chain was calibrated before every measuring cycle by B&K 4223 pistonphone which generates the pressure level of 162dB re 1µPa in the air on the frequency of 250Hz. The calibration procedure is simple: the hydrophone is fitted into the coupler UA 0547 and the control switch pushed to the "On" position, so the piston phone produces a constant sound pressure level on the surface of the hydrophone.

The river bottom sediment was primarily composed as a mixture of sand, silt, and mud.

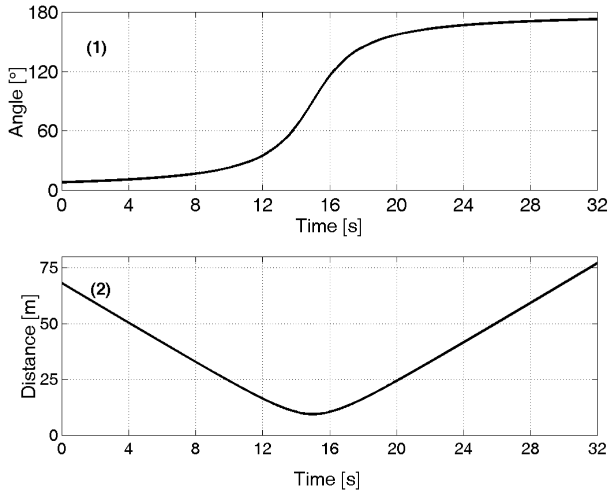

Figure 2. Position of the ship when the location of the hydrophone is taken as reference.

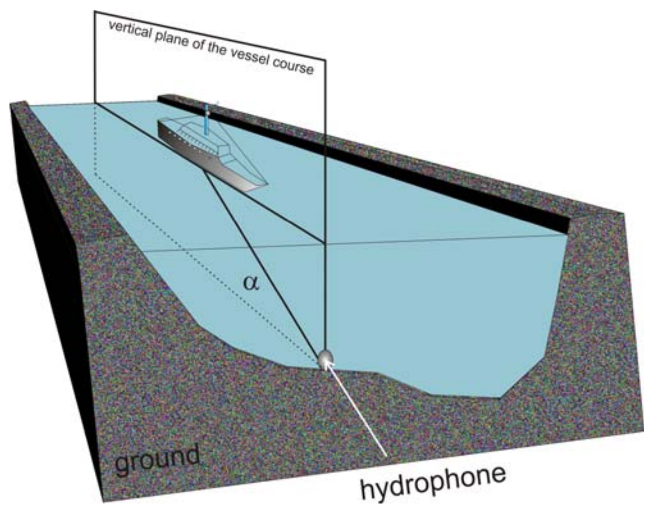

Figure 3. Hydroacoustic test range at the river

Radiated acoustic noise of the ships in the river water environment, as elaborated previously, is recorded using sensitive pressure transducer, which transforms hydroacoustic pressure fluctuations into electrical signal whose amplitude is proportional to the pressure fluctuations. Hydrophone, type B&K 8104, was used throughout all measurements of the ship radiated noise.

Typical shape of the electric signal obtained during ship passing above the hydrophone is shown in Fig.4. Time duration of the recorded signal was about thirty seconds. During that period of time, the radiated acoustic noise was at a relatively high level. It is obvious that a region exists where the radiated noise is particularly pronounced. That time region is between the eleventh and the seventeenth second, when the ship position is in the vicinity of the closest point of approach, CPA position, with regards to the submerged hydrophone.

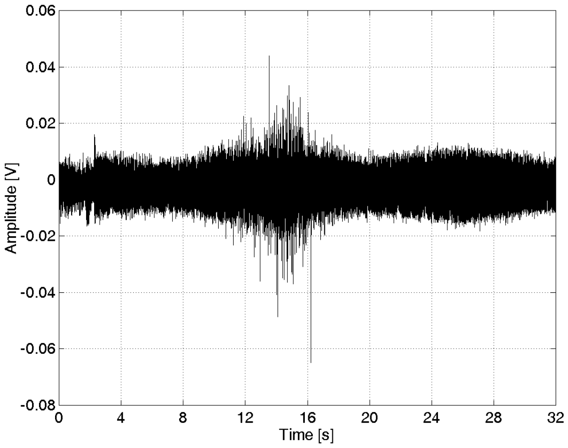

Figure 4. Amplitude of hydroacustic noise of the vessel

Also, it is noticeable that a short time period exists with very large amplitudes of acoustic signal, particularly when the ship reaches the CPA region. That is the consequence of complex processes that occur, such as superposition of the acoustic rays reflected from the riverbed and bottom of the ship hull.

Time fluctuations of the amplitudes of the recorded acoustic signal causes time fluctuations of the spectrum pressure levels of the ship radiated hydroacoustic noise, too. Fig.5 shows a spectrogram of the hydro acoustic characteristics of the passing ship. Variability of the source-receiver geometry influences the characteristics of the spectrogram of the radiated noise of the vessel.

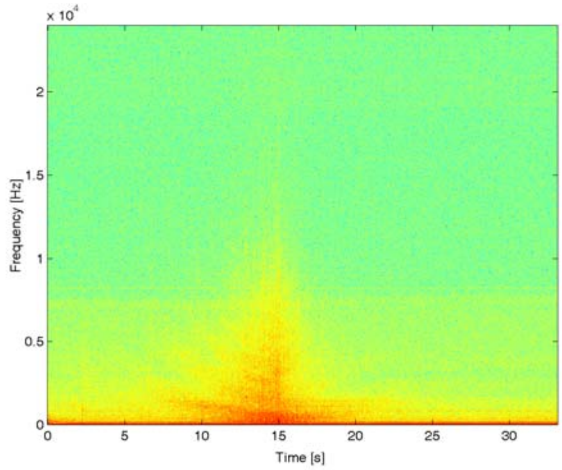

Figure 5. Spectrogram of hydroacoustic noise signal.

At the CPA time region, the levels of the spectrum possess higher spectrum values. Frequency content of the signal is filled in the way that higher spectrum pressure levels are better emphasized. Spectrogram in Fig.5 is obtained on the bases of the noise signal presented in Fig 4. The length of DFT blocks was 4096 points with no overlap, window was Hanning, and sampling frequency was 48000Hz.

On the bases of the result presented in Fig.4, it is possible to conclude that the most pronounced frequency content of the signal exists during time period of about ten seconds when the ship is closest to the measuring hydrophone, or more exactly, in the neighborhood of CPA point. It does not mean, however, that such frequency content of acoustic noise is not possible to obtain when measuring is done on greater distances, but the observed local maximum will be on a lower level. Very pronounced tonal spectral component exists in low frequency range as a consequence of work of the ship propulsion system - motor.

Spectrum pressure levels of the radiated ship hydroacoustic noise with better resolution are presented in Fig.6.

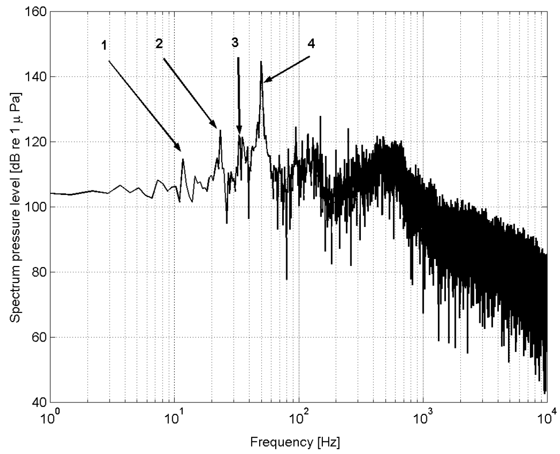

Figure 6. Spectrum of the hydroacoustic noise signal at CPA position

To get better insight into the spectrum of the radiated noise, the spectrum of the noise with frequency hop of about 0.7324Hz is presented in Fig.6. At low frequency band, a few tonal spectrum components exist and they are marked with numbers from 1 to 4 with corresponding frequencies of 11, 22, 33 and 50Hz, respectively.

The source spectrum, $SL(f)$, of the vessel at reference of 1m is determined according to

$$SL(f) = RL(f) + TL(f), \tag{1}$$

where $RL(f)$ is radiated noise level in decibels, and $TL(f)$ transmission losses in decibels which include absorption and spreading.

Radiated noise spectra were obtained from the time series of the measured noise signal. Usually, set of standard corrections to hydrophone signals received from a vessel are made. The factors that affect the received signals fall into two categories. The first category is composed from factors that are fully under the control of the operator. These cover items such as vessel position during measurement, hydrophone sensitivity and directivity and other system related factors. Secondly, there are factors which are beyond the control of the operator and whose details often remain unknown. These include the local propagation conditions, the variability of this propagation in both time and space, the nature of both the riverbed and river surface and any effects presented by the local ambient noise.

The origin of these tonal components in the spectrum pressure levels is not possible to explain without further investigations. Namely, to get reliable interpretation of this phenomenon, it is necessary to analyze the vibration sources on the ship while it is moving, simultaneously measuring the radiated hydro-acoustic noise.

Namely, simultaneously with acoustic measurements, the measurements of vibration motions at the selected points of the ship structure were done. The measurements were done using B&K DeltaTron vibration transducers, PULSE™ 3560D, analyzer with six input channels type B&K 3032 and control and analysis of the signals was performed using software PULSE LabShop [6]. PULSE™

3560D systems can be used for any type of noise and vibration analysis including single-input multiple-output (SIMO) or multiple-input multiple-output (MIMO) frequency response calculations for traditional modal analysis, or time data acquisition for operational modal analysis. The analysis of the vibrations (see Figures 7 and 8) was done using DFFT, Hanning window and 50 averages.

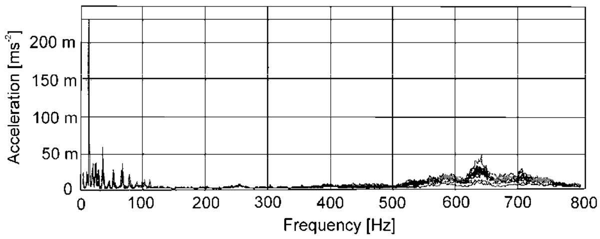

Figure 7. Vibration spectrum, vertical axis at ship's bow peak [6]

In Fig.7, the spectrum of the vibrations in vertical axis measured at ship's bow peak is presented. The existence of tonal components at frequencies of 11, 22, 33, 50 … Hz is obvious.

Another vibration transducer was mounted on the home site of the main motor. The spectrum of the vibrations in the vertical axis is shown in Fig.8. The same procedure of measuring and analysis of vibration signal was used.

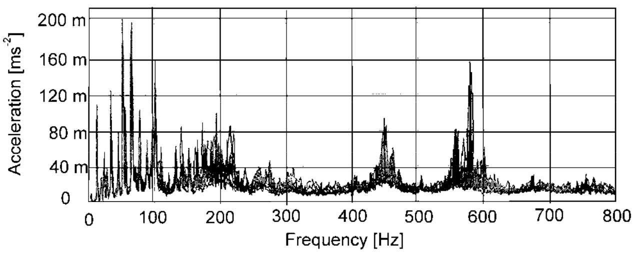

Figure 8. Vibration spectrum, vertical axis at home site of the main motor [6]

The most pronounced vibration component on the vertical axis at home site of the main motor is at frequency of 50Hz.

Limitations of classical spectrum estimation of the ship noise

The analysis of underwater systems involves the consideration of signals in the frequency domain. Transformation time domain functions into the frequency domain are performed using Fourier analysis. Stationary random process can be characterized by means of a spectral density function. Namely, this function provides information concerning the power as a function of frequency for the stationary process.

When dealing with actual physical phenomena and practical systems, the constraint about finite length record function is always present. Namely, for systems operating in real time, the record of interesting signals is limited in the time domain. Therefore, practical spectral estimates must be limited to a finite frequency range. Also, systems using digital hardware, computers and other devices, require that the functions processed be converted to a discrete sets of numbers, or simple values.

Subsequent digitalization of the signal was performed with a sampling rate of *Fs*=48.000Hz, without previous filtrating. Recording of the radiated noise was done during time period of about thirty seconds in such a way that CPA of the ship was in the middle of that time period.

Classical spectral estimation understands the need for windowing the analyzed signal. That means that all unobserved samples are effectively zero, whether or not this is true. The transform of the observed finite sequence is a distorted version of the infinite sequence transform. Many discrete time windows exist, such as: rectangle (uniform), triangle (*Bartlett*), raised cosine (*Hamming*), weighted cosines, and other. The frequency response of the rectangular window has the narrowest main lobe among the windows mentioned. The strategy for window selection is dictated by a trade-off between bias due to interferers in nearby side lobes versus bias due interferers in distant side lobes [7].

Parametric models of the ship underwater noise

A time-series model that approximates many discrete-time deterministic and stochastic processes encountered in practice is represented by the filter linear difference equation (2), of complex coefficients.

$$\begin{aligned} x[n] &= -\sum_{k=1}^{p} a[k]\cdot x[n-k] + \sum_{k=0}^{q} b[k]\cdot u[n-k] = \\ &= \sum_{k=0}^{\infty} h[k]\cdot u[n-k], \quad \left(h[k]=0\ \forall\ k<0\right) \end{aligned} \tag{2}$$

In eq. (2), $x[n]$ is the output sequence of the causal filter ($h[k]$=0 for k<0) that models the observed data, and $u[n]$ is an input driving sequence (white noise sequence) [7].

This form of the difference equation enables calculation of the output signal on the bases of p preliminary samples of the output signal x and q preliminary values of the input signal u.

The parametric models of random processes enable achieving better power spectral estimators than by using classical spectral approach. Namely, such models allow for a more realistic assumptions about the data outside the window where according to discrete Fourier transform concept, the zero assumption is valid.

Models of random process, based on parameters such as the autoregressive (AR) process model, the moving average (MA) process model and autoregressive-moving average (ARMA) process model, belong to the special class of models, driven by white noise processes and possessing rational systems functions. The need for window functions is eliminated, along with their distorting impact. Therefore, the degree of improvement in resolution and spectral fidelity is possible to expect.

The roots of

$$A(z) = 1 + a(1)z^{-1} + \cdots + a(p)z^{-p} \tag{3}$$

denote the poles of the ARMA(p, q) process, and roots of

$$B(z) = 1 + b(1)z^{-1} + \cdots b(q)z^{-q} \tag{4}$$

are the zeros.

The parametric approach to spectral estimation involves three steps:

- first, selection of the appropriate parametric time-series;
- second, estimation of the parameters of the selected model, and

- third, inserting the estimated parameters into the theoretical power spectral expression appropriate for the model.

Transfer functions of the digital filters are represented by the following equations:

$$H_{AR}(z) = \frac{1}{1+\sum_{i=1}^{p} a_i z^{-i}}$$
$$H_{MA}(z) = 1+\sum_{j=1}^{q} b_j z^{-j} \quad (5)$$
$$H_{ARMA}(z) = \frac{1+\sum_{j=1}^{q} b_j z^{-j}}{1+\sum_{i=1}^{p} a_i z^{-i}}$$

Filter AR is all-zero filter and Finite Impulse Response (FIR), see Fig.9. If for the generation of the signal the filter shown in the figure is used then its output is a linear combination of current and q previous values of the impulse, and the name of this model is Moving Average (MA). The combination of these two models gives Auto Regressive Moving Average or (ARMA). The problem of finding the model parameters, implies solving the appropriate system of equations. Namely, the problem of the AR parameters lead to the problem of solving a linear system of equations, but the problem of MA parameters means solving the system of non-linear equations. Very effective algorithm exists for solving the AR parameters such as the *Yule-Walker*, harmonic, or Burg, algorithm, geometric algorithm and others.

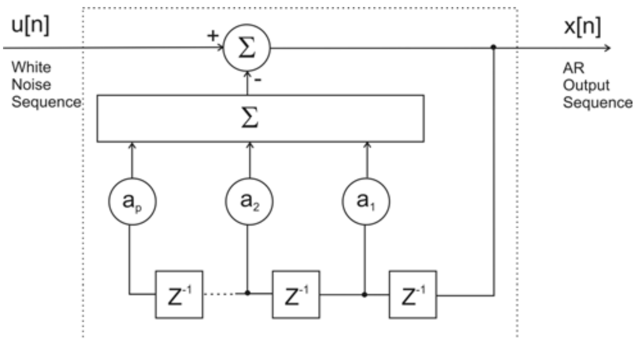

Figure 9. Model of the AR filter [7]

The autoregressive spectral estimate has received significant attention in the technical references, being a very interesting time-series model. Mainly two reasons are important for such assertion. Firstly, autoregressive spectra tend to have sharp peaks, a feature that is characteristics for high-resolution spectral estimates. The possibility to estimate AR parameters solving a set of linear equations makes the second reason. Algorithm for AR power spectral density estimate consists of a few steps that are possible to systematize in the following manner:

- acquiring data (N samples);
- trend removal (optional);
- selecting the AR model order;
- estimating AR parameters (*Yule-Walker* method, *Burg* method, covariance method, modified covariance method);
- computing AR PSD estimate, and
- order closing.

It is important to emphasize that noise corrupts the data samples, degrading the performance and resolution of AR spectral estimates.

Moving average (MA) models (see Fig.10) are appropriate for the processes that have broad peaks or sharp nulls in their spectra. Power spectral density, estimated by MA model, does not model narrowband spectra well and therefore it is not high-resolution spectral estimator. To estimate MA parameters it is necessary to solve a nonlinear convolution equation. Solutions of that equation often involve spectral factorizations techniques.

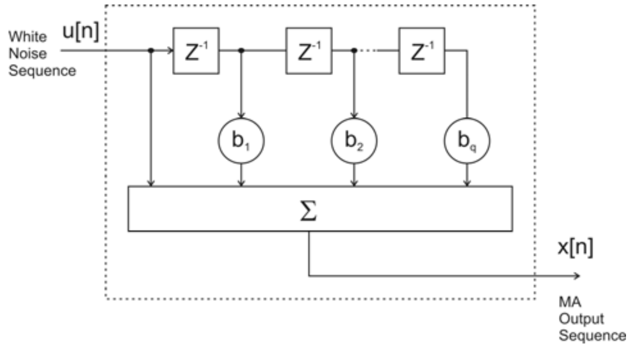

Figure 10. Model of the MA filter [7]

ARMA processes, which are presented in Fig.11, are possible to solve by simultaneous estimation of the AR and MA parameters. However, selecting the AR and MA orders of an ARMA time series model is not a simple procedure. References do not offer adequate recommendations for order selection, except for a relatively few simple cases. Therefore, *Akaike* Information Criterion (AIC) for an ARMA has been one of the techniques used most often. This criterion has the form [7]:

$$AIC[p,q] = N \cdot \ln\left(\hat{\rho}_{pq}\right) + 2(p+q) \quad (6)$$

where, $\hat{\rho}_{pq}$ is an estimate of the input white noise variance of the assumed ARMA (p, q) model.

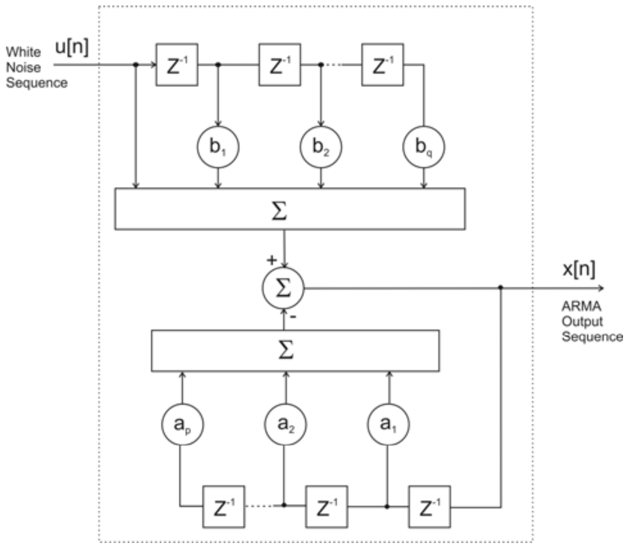

Figure 11. Model of the ARMA filter [7]

Parametric approach using AR, MA or ARMA model of a finite number of parameters is possible to express in terms of the other two models, but it is necessary to use many more parameters, or the order of the model should be large enough. For instance, an ARMA or MA process can be represented by a unique AR model of infinite order. This is important because AR model is a particular case for which many efficient algorithms exist.

The problem of selecting the model type has recently been solved by introducing an automatic selection algorithm which is denoted as the *ARMAsel* model [8]. Namely, the choice between the three mentioned models can only be done by using a statistical criterion. The type of the model is selected based on the data, not a subjective choice of the experimenter. For each model type the order selection is done by statistics.

AR and MA parameters of the noise signal of the vessel in the river environment

The signal of the ship passing characteristics (see Fig.4) is analyzed using parametric models. The whole signal is divided into non-overlapping blocks of the same length. AR and MA parameters are estimated on segments. The procedure enables obtaining their time distribution. The order of AR and MA parameters was limited to 100.

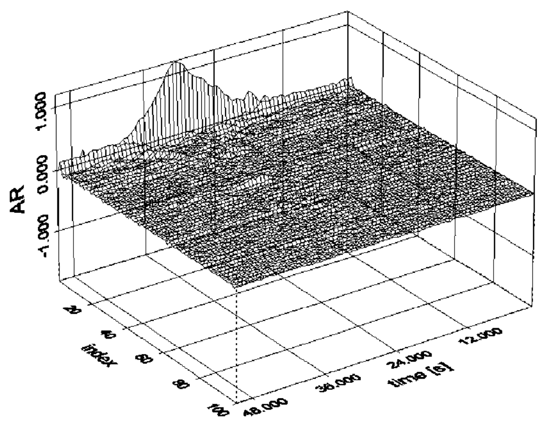

Figure 12. Time distribution of the AR parameters of the hydroacoustic signal

Time distribution of the AR parameters is shown in Fig. 12. According to the results presented there, it is not necessary to have such a great order of AR parameters.

The results of the analysis of MA parameters are shown in Fig.13. As in the previous example, the order of MA parameters was 100. Radiated acoustic noise energy of the vessel is predominantly distributed in the observed frequency range.

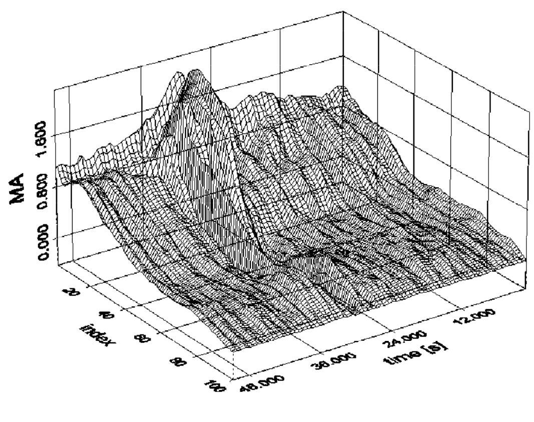

Figure 13. Time distribution of the MA parameters of the hydroacoustic signal

Time distribution of MA parameters is well correlated with the structure of the spectrogram in Fig.5. The order of the MA estimate is in accordance with the spectrum content of the acoustic noise signal.

Higher order spectral analysis of the ship's noise

One of the purposes of this work is to test all available methods for classification of local maximums in the spectrum of the ship radiated hydroacustic noise. Polyspectra analysis is introduced on the bases of statistical methods. Starting point are the cumulants, which are defined using higher order moments.

Polyspectra are defined through series of cumulants and their *Fourier* transform. The second order cumulant, equation (7), is defined in the following way [9, 14]:

$$C_{2x}(k) = E\left\{x^*(n)\cdot x(n+k)\right\}. \qquad (7)$$

Bispectrum is defined as two frequencies Fourier transform of the third order cumulant, i.e. the bispectrum is equivalent to the third-order polyspectrum.

$$S_{3x}(f_1,f_2) = \sum_{k=-\infty}^{+\infty}\sum_{l=-\infty}^{+\infty} C_{3x}(k,l)\cdot e^{-j2\pi f_1 k}\cdot e^{-j2\pi f_2 l}. \qquad (8)$$

A non-redundant region of support for the bispectrum is the triangle with vertices (0,0), ($1/3f_s$, $1/3f_s$) and ($1/2f_s$, 0), where f_s is the sampling frequency.

In the case of the real and stationary processes, symmetric properties of the cumulants lead to the symmetric properties of their polyspectrums. The symmetries of the third-order cumulant are:

$$C_{3x}(k,l) = C_{3x}(l,k) = C_{3x}(-k,l-k) = C_{3x}(k-l,-l). \qquad (9)$$

The symmetries of the bispectrum S_{3x} are:

$$\begin{aligned} S_{3x}(f_1,f_2) &= S_{3x}(f_2,f_1) = \\ S_{3x}(f_1,-f_1-f_2) &= S_{3x}^*(-f_1,-f_2). \end{aligned} \qquad (10)$$

The symmetry relations indicate that the bispectrum is completely defined over each of the six regions shown in Fig.14.

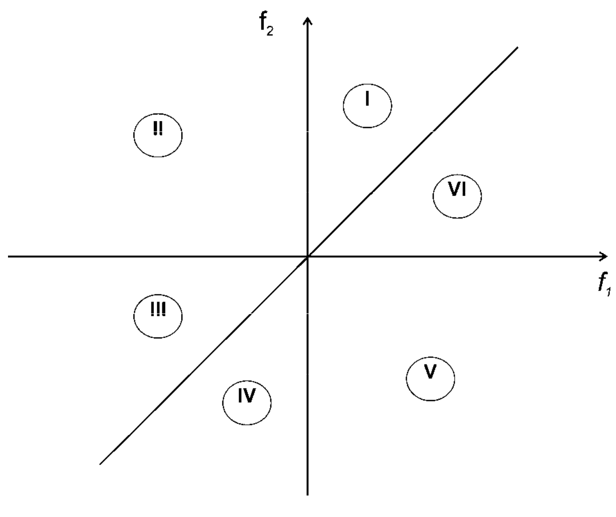

Figure 14. Symmetry of the bispectrum

Power spectrum of the signal does not possess any information about the phase, but the information about the phase exists in the spectrums of higher order.

Therefore, using polyspectra is important whenever the signal is non-Gaussian or when the characteristics of the signal are the consequence of non-linear effects.

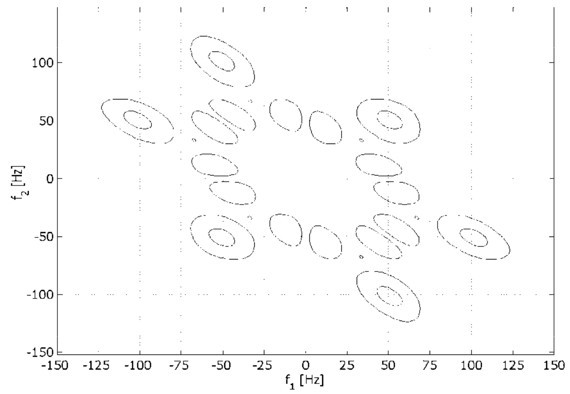

Figure 15. Bispectrum of the hydroacoustic noise before the CPA point is reached

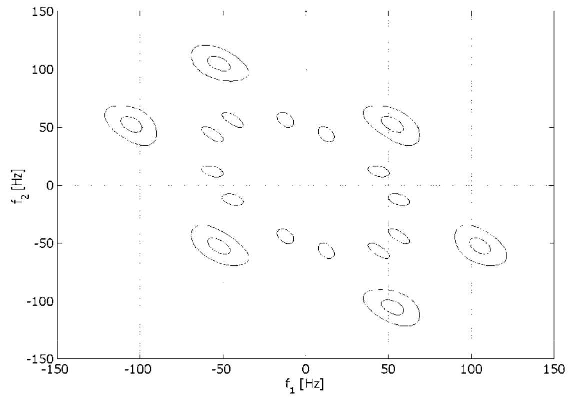

Figure 16. Bispectrum of the hydroacoustic noise at the CPA point

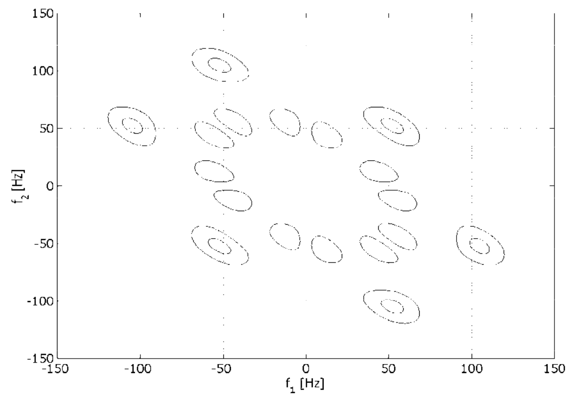

Figure 17. Bispectrum of the hydroacustic noise signal when the CPA point is passed

The results of the bispectrum analysis of the hydroacustic noise, Figures 15 - 17, unambiguously show the dominant role of vibration of the main motor on the characteristics of the radiated hydroacoustic noise of the ship, due to the fact that frequency of 50Hz is sharply emphasized. In addition, some low frequency components originate from the river vibration modes [15].

Conclusion

Military vessels operate under a risk in the water environments where the possibility to be damaged by the naval mines exists. Therefore, it is necessary to know the characteristics of the radiated acoustic noise of the vessels. Based on the measured data, it is necessary to apply the anticipated procedures, in order to reduce the increased and unwanted self-acoustic noise. In other words, the so called, "acoustic hygiene", is necessary to be monitored periodically. The best way to do this is to control acoustic noise characteristics of the vessels at special acoustic test ranges, like those in Heggernes.

This work presents the results of the analysis of the radiated hydroacoustic noise of the vessel that was obtained in the river test range. The analysis encompasses spectrum level estimates, bispectrum analysis, and parametric modeling of the acoustic spectra.

Naval mines are triggered by various combinations of the multiple influence signals emanated from vessels, too. Among them, the most important influences originate from hydroacoustic noise. Naval influence mines have been used in many conflicts over the last two centuries. The underwater acoustic signals which are radiated from the vessels are used for active and passive location and ranging, as well as for the purpose of identifying the vessel. The susceptibility of individual naval ships to detection and destruction by an influence mine can be reduced, first by measuring the ship's underwater signatures and then by implementing an appropriate signature reduction strategy. This paper focuses on the aspect of underwater acoustic signatures of the vessels in the river water environment.

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Received: 25.11.2006.

Spektralna karakterizacija hidroakustičkog polja plovnih objekata u rečnoj sredini

Akustički šum koga plovni objekti generišu tokom kretanja na poligonu na reci je predmet ovog rada. Hidroakustičko polje plovnog objekta je analizirano pomoću nekoliko metoda. Analize su provedene u vremenskom i frekvencijskom domenu. Akustički signali su analizirani korišćenjem klasičnog koncepta spektralne analize, parametarskim modelima stohastičkih procesa i korišćenjem bispektralne analize. Posebno je bilo od interesa identifikovati uskopojasne doprinose ukupnom spektru brodskog hidroakustičkog šuma.

Ključne reči: **hidroakustika, hidroakustičko polje, hidroakustički šum, brod, reka, hidroakustički signal, spektar signala, bispektar, identifikacija signala.**

Спектральная характеризация гидроакустического поля судоходных объектов в речной среде

Предметом настоящей работы является акустический шум, который судоходные объекты генерируют в течении движения на полигоне на реке. Гидроакустическое поле судоходных объектов анализировано при помощи нескольких методов. Анализы проведены во временных и частотных областях. Акустические сигналы анализированны пользованием классического концепта спектрального анализа, параметрическими моделями стохастических поцессов и пользованием биспектрального анализа. Особенно было полезно опознавать узкополосные вклады совокупному спектру судового гидроакустического шума.

Ключевые слова: судовой шум, полигон, спектр, биспектр, опознавание, река, гидроакустика, гидроакустическое поле, гидроакустический шум, судно, гидроакустический сигнал, спектр сигналов, опознавание сигналов.

La caractérisation spectrale du champ hydroacoustique des vaisseaux dans l'environement fluvial

Le bruit acoustique, produit par les vaisseaux pendant le mouvement sur le polygone fluvial, fait l'objet de ce travail. Le champ hydroacoustique du vaisseau est analysé au moyen de plusieurs méthodes. Les analyses ont été effectuées dans deux domaines : temps et fréquence. Les signaux acoustiques ont été étudiés à l'aide du concept classique de l'analyse spectrale, par les modèles paramétriques des procès stochastiques et en appliquant l'analyse bispectrale. L'intérêt particulier était l'identification de la contribution des bandes étroites dans la spectre total du bruit hydroacoustique du vaisseau.

***Mots clés*: hydroacoustique, champ hydroacoustique, bruit hydroacoustique, rivière, signal hydroacoustique, spectre du signal, bispectre, identification du signal.**