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Bispectral analysis of the noise of navigable objects

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Passive hydroacoustic (HA) detection of navigable objects means a possibility of narrow band frequency separation of spectral components in the spectrum of hydroacoustic noise provoqued by various aggregates and processes during object moving in water. The most important role in noise generation have the main and auxiliary motors, the propeller, the pumps and other processes. In order to detect navigable objects, it is necessary to apply the techniques of the bispectral analysis of hydroacoustic signals generated in water as a result of moving of navigable objects. In this work the passing hydroacoustic characteristics of a navigable object are presented.

Key words: **hydroacoustic detection, hydroacoustic noise of navigable objects, bispectrum, navigable object.**

Used marks and symbols

$A(z)$	– characteristic polynomial of the *ARMA* model, pole definition
a_i	– parameter of the *AR* model
$B(z)$	– characteristic polynomial of the *ARMA* model, zeros definition
$\hat{B}(k,l)$	– bispectrum of limited time series
b_i	– parameter of the *MA* model
C_{kx}	– cumulant of order k
$E\,[x(n)]$	– operator of the mean value
f	– frequency
F_s	– sampling frequency
K	– the number of non-overlapping blocks
M_{jx}	– moment order j of the signal x
S_{kx}	– polyspectrum order k of the signal x
p	– order of the *AR* model
q	– order of the *MA* model
$X_j(k)$	– discrete Fourier transform in M points of the time series
$x(n)$	– time series, digital form of the analog signal
$y(n)$	– filter output
$\Phi_y(\omega)$	spectral density function of the filter output
φ	– phase
σ	– variance

Introduction

HYDROACOUSTIC signals radiated by navigable objects are used for identification, location and determination of the parameters of navigable object movement. Bispectrum, i.e. the bispectral analysis is used as a generally accepted method for the analysis of periodic signals in many fields, such as: medicine – heart diagnostics, supervision of machinery work, tides waves [1-3], etc.

Electrical signals generated by a hydrophone during navigable object passing along the straight course in the shallow water with constant velocity is analyzed in this work. Estimating the parameters of hydroacoustic signals is of particular interest in case when we wish to achieve a classification of hydroacoustic signals of navigable objects, on the move when mechanical rotation predominantly defines characteristics of radiated noise signals. A standard navigable object with a conventional configuration of the propulsion system is analyzed. It is well known that relatively good results could be accomplished by using the spectral analysis for the signal analysis. The spectral analysis enables estimating the frequency distribution of the signal energy but if we wish to establish a form of the phase coupling between spectral components it is necessary to use the techniques of the spectral analysis of a higher order. The bispectral signal analysis gives answers to this question. On the basis of the bispectral analysis it is possible to determine the phase coupling of the signal spectral components. Existence of the phase coupling of the local spectral maximums enables various physical interpretations of their origin. For instance, it is possible to recognize the harmonics generated by the propeller from those generated by the motor. The possibility to accomplish this task is the key for a successful classification of noise sources on the basis of their spectral characteristics. In this way it is possible to attribute a particular group of harmonics to a particular propeller or some other group of harmonics to other particular propeller.

Methods for spectrum analysis

There are many approaches in the analysis of time series and among them it is necessary to point out those intended for spectral characteristics estimation of the signals, in particular those which give answers about frequency distribution of the signal energy. Power spectral estimation could be done using different methods, which can be classified in this way:

1. non-parametric or conventional methods,
2. parametric methods or methods based on models, and
3. methods based on criterions.

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The first group of methods is divided into two subgroups: direct methods, based on the Fourier transform of the signal and indirect, ones based on calculating the Fourier transform of the autocorrelation data series. The conventional methods are easy to implement and understand. They have certain limitations reflecting in a relatively weak possibility to separate two close frequencies in the spectrum. The problem of separation of close frequencies is outstanding when a time series is relatively small. In the case of the stochastic process analysis, the application of direct methods in the spectrum analysis means using relatively long time segments of the signal and in this way the error in spectrum estimation would be minimal [4].

Today there are several parametric methods for spectrum estimation depending on a used model. The most used models are:

- *AR* (Autoregressive);
- *MA* (Moving Average);
- The combination of the two previous models *ARMA*, (Autoregressive Moving Average);
- Models based on eigenvalues such as *MUSIC, Min-Norm*, etc.

The parametric spectrum estimation is very useful but under some circumstances it leads to an incomplete spectrum estimate. The starting point for introducing parametric methods is a hypothesis that a signal *x(n)* depends on a limited number of parameters and all statistic parameters are possible to be expressed using them.

Today there are several methods based on the application of some criterions and among them Burg's algorithm of maximum entropy should be pointed out as well as the method based on Capon's algorithm of maximum likelihood or minimum variance. Burg's criterion gives better frequency resolution than Capon's one when the signal noise ratio is higher than one [4].

The Fourier transform of the signal at a particular frequency could be considered as a filter letting signal components pass through this frequency but rejecting other frequencies. However, the spectrum estimation in this way suffers from a lack of data on the edge of the data segment.

ARMA model of the signal

ARMA models are used for parametric description of the signal spectrum, which, besides harmonic components, has additive white noise. A fundamental problem is to determine the order of the *ARMA* model as well as the parameters. Parametric models do not need the introduction of the window concept. Today there are reliable algorithms for parametric estimation of the time series that are independent of their size. The importance of the parametric models is in the fact that on the basis of autocorrelation sequence nothing cannot be concluded about non-linearity of the signal, although it is well-known that a radiated HA noise of navigable object is characteristic by its nonlinearity due to mechanisms of its origin. In the case of stationary stochastic process there are a few ways to generate time series. The only problem is a choice of an adequate model. There is no automatic procedure for selecting a model with good results. One of possible ways for generating time series is based on filter application. Namely, it is well-known that in the beginning of the last century it was suggested that a time series is possible to be generated at the filter output when white noise *x(n)* is applied at the input with a zero mean value and a constant variance [5]:

$$E[x(n)] = 0$$
$$E[x(n)x(k)] = \begin{cases} \sigma_x{}^2, n = k \\ 0, \quad n \neq k \end{cases} \tag{1}$$

Three groups of filters are used, so it is possible to create the following outputs y

$$y(n) + a_1 y(n-1) + \cdots + a_p y(n-p) = x(t) \tag{2}$$

$$y(n) = x(n) + b_1 x(n-1) + \cdots + b_q x(n-q) \tag{3}$$

$$\begin{aligned} y(n) = -a_1 y(n-1) - \cdots - a_p y(n-p) + \\ + x(n) + b_1 x(n-1) + \cdots + b_q x(n-q) \end{aligned} \tag{4}$$

The process described by eq.(2) is called auto regressive or the *AR* process. Eq.(3) describes a model with a moving average mean value, i.e. the *MA* process. The combination of these two models is represented by eq.(4) and is called the *ARMA (Auto Regressive Moving Average)* model. The basic characteristics of these models are parameters, poles, reflection coefficients, correlation coefficients and roots. By using them, it possible to describe the *ARMA* process on the basis of a limited number of parameters. The roots of the polynomial

$$A(z) = 1 + a_1 z^{-1} + \cdots + a_p z^{-p} \tag{5}$$

define the poles of the *ARMA(p,q)* process and the roots of the polynomial

$$B(z) = 1 + b_1 z^{-1} + \cdots + b_q z^{-q} \tag{6}$$

determine zeros.

The process is stationary if all poles are within a circle with the radius equal to one and the opposite claim is that all zeros are within a circle whith the radius one, as well.

By definition, the last parameter of the stationary *AR* model of *p* order*,* is called reflection coefficient. The reflection coefficient of the stationary process is (-1,1).

The power spectral density can be calculated on the basis of model parameters using the following equation

$$\Phi_y(\omega) = \frac{\dfrac{\sigma_\varepsilon{}^2}{2\pi} \left| 1 + \sum_{i=1}^{q} b_i \exp(-j\omega_i) \right|^2}{\left| 1 + \sum_{i=1}^{p} a_i \exp(-j\omega_i) \right|^2} \tag{7}$$

The covariance function is an inverse Fourier transform of the previous equation. Also, it should be pointed out that there are parametric relations for calculating the covariance function.

Experiment

The measurements of the radiated HA noise of a navigable object are done in the water of the south Adriatic sea, where the depths of the sea are constant, about 40 m. The navigable object was moving along the straight course with a constant velocity of about 10 knots, until the hydrophone of the *B&K 8104* type, was dipped into a depth of 2 m. The electrical signal from the hydrophone is amplified by the *B&K 2635* conditioning amplifier and then recorded using the *B&K 7004* type recorder. Subsequent digitalization of the signal was performed with a sampling rate F_s = 20 kHz, without previous filtrating. Sampling speed was slightly magnified, regarding that all processes of interest were in a frequency range below 3000 Hz.

Three groups of data were used for the analysis. The first group contained data gathered during the approach of the navigable object, point 1 in Fig.1. The second group contained data gathered during the departure of the navigable object from the measuring point, point 3 in Fig.1, and the third group was made of data gathered when the navigable object was closest to the measuring point, point 2 in Fig.1. In the literature, point 2 is marked as the *CPA (Closest Point of Approach)*.

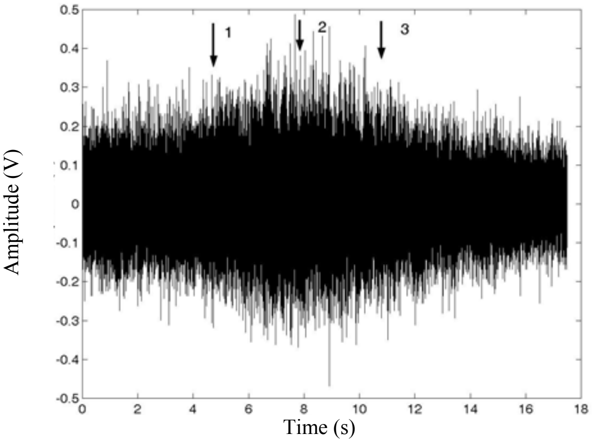

Figure 1. Passing HA characteristics

The bispectral analysis method

The sufficient and necessary condition for the existence of the power spectrum is that the autocorrelation sum is absolutely convergent. The power spectrum is a real, non-negative value, symmetrical in relation to the frequency. The moments of a higher order are a natural generalization of the autocorrelation, while the cumulants of the specific order are specific nonlinear combinations of the moments. The higher order cumulants point out to the existence of non-linearity and the cumulants of a particular order are defined in particular. For example, the cumulant of the first order is a mean value, while the cumulants of higher orders are defined in the following way

$$C_{2x}(k) = E\{x^*(n)x(n+k)\} \tag{8}$$

$$C_{3x}(k,l) = E\{x^*(n)x(n+k)x(n+l)\} \tag{9}$$

$$\begin{aligned} C_{4x}(k,l,m) = {} & E\{x^*(n)x(n+k)x(n+l)x^*(n+m)\} \\ & -C_{2x}(k)C_{2x}(l-m)-C_{2x}(l)C_{2x}(k-m)- \\ & -M^*{}_{2x}(m)M_{2x}(k-l) \end{aligned} \tag{10}$$

The cumulants of all orders have the additional property and that fact in many cases simplifies the analysis procedure. Also, the cumulants of stationary real processes are symmetrical to their arguments.

Polyspectra are defined through series of cumulants and their Fourier transform. The polyspectra of the first, second and third order are defined in the following way

$$S_{2x}(f) = \sum_{k=-\infty}^{\infty} C_{2x}(k)e^{-j2\pi fk} \tag{11}$$

$$S_{3x}(f_1,f_2) = \sum_{k=-\infty}^{\infty}\sum_{l=-\infty}^{\infty} C_{3x}(k,l)e^{-j2\pi f_1 k}e^{-j2\pi f_2 l} \tag{12}$$

$$S_{4x}(f_1,f_2,f_3) = \sum_{k,l,m=-\infty}^{\infty} C_{4x}(k,l,m)e^{-j2\pi(f_1k+f_2l+f_3m)} \tag{13}$$

wich define power spectrum, bispectrum and trispectrum, respectively.

The basic area of the bispectrum in the (f_1, f_2) plane is defined by the triangle vertices $(0,0)$,$\left(\frac{1}{3},\frac{1}{3}\right)$ and $\left(\frac{1}{2},0\right)$in the case of the normalized sampling frequency F_s=1 Hz.

The bispectrum of the discrete time series *x(n)*, which corresponds to the HA signal of the radiated noise of the navigable object, could be calculated using the following equation [6,7]

$$\hat{B}(k,l) = \frac{1}{K}\sum_{j=1}^{K} X_j(k)X_j(l)X_j^*(k+l) \tag{14}$$

where $X_j(k)$ is the discrete Fourier transform in *M* points of the time series and *K* is a number of non-overlapping blocks. In this way the bispectrum at discrete frequencies is defined

$$(f_1,f_2) = (k\Delta f, l\Delta f) \tag{15}$$

where the frequency difference Δf is defined as a quotient of the sampling frequency and the number of points of the discrete Fourier transform. The practical choice of these parameters enabled the bispectral analysis with a frequency resolution of about 5 Hz. The number of points of the discrete Fourier transform was 4096. The calculation of the bispectrum with such a resolution is computationally demanding task. Because of that, the indirect procedure with *ARMA* models was defined and the bispectrum was calculated on the basis of *ARMA* parameters [4].

Using such procedures was justified because the HA signal has a very distinct structure of local extremes in the spectrum within the observed frequencies, so with a choice of an adequate order of *ARMA* model it was possible to optimize computer time. The order of the *ARMA* models *(p,q)* did not exceed 100.

The *ARMA* parameters were determined by the *MATLAB* function *armasel.m*, (by *P.M.T. Brorensen*), version [2001 3 14 22 5 14] [8], and then the bispectrum was calculated..

The results of the calculations are presented in Figs.2 to 10. The analysis shows the existence of sharp local maximums and the harmonics of this basic frequency f_0, pointing out at the existence of the phase coupling. Besides the frequency of the primary harmonic f_0, it is possible to notice higher harmonics with the frequencies $f_0 + f_0$, f_0 +2 f_0 or $f_3 = f_1 + f_2$ and the phases $\phi_3 = \phi_1 + \phi_2$ in the case of quadratic coupling.

The example of the existence of phase coupling is the frequency of 108 Hz, with the harmonics of 220 Hz and 434 Hz, Fig.2.

The bispectral analysis was performed at three chosen points on the ship passing characteristic, points 1,2 and 3, Fig.1. The results show that the ship acoustic noise has very emphasized space characteristics which is possible to be seen very clearly using only one sensor. Point 1 is characterized by a very emphasized influence of the bow, point 2 is distinctive by equal influence of the bow and the stern and point 3 is distinctive by stern influence. To confirm these results, the additional analysis was done.

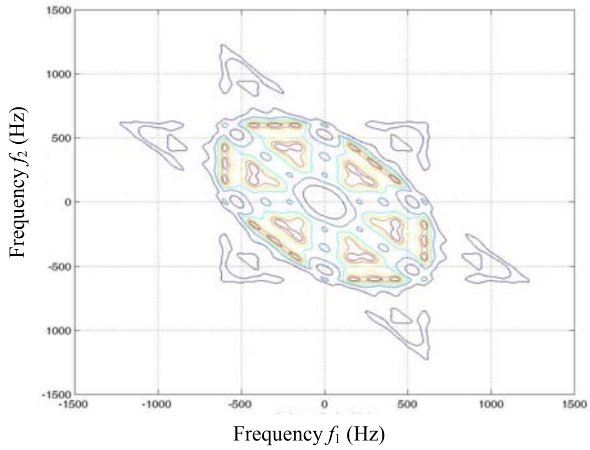

Figure 2. The bispectrum, position 1, driving in the course

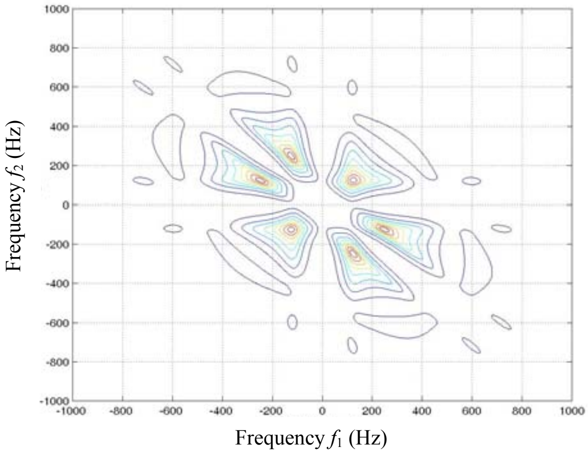

Figure 3. The bispectrum, position 2, driving in the course

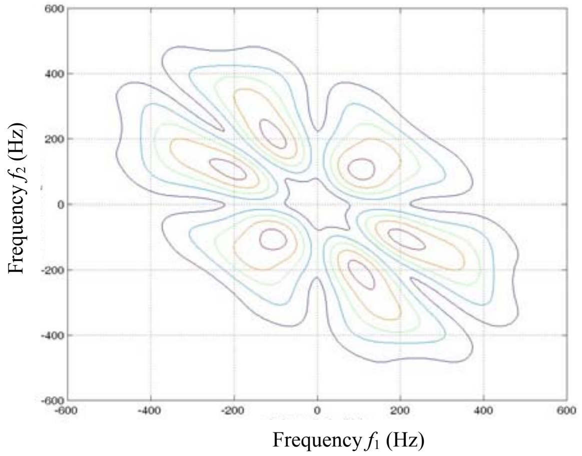

Figure 4. The bispectrum, position 3, driving in the course

The whole analysis was done for two cases: first, the ship moved in course and second, the ship moved in the opposite direction (Figs.5,6 and 7,) and the same results were obtained.

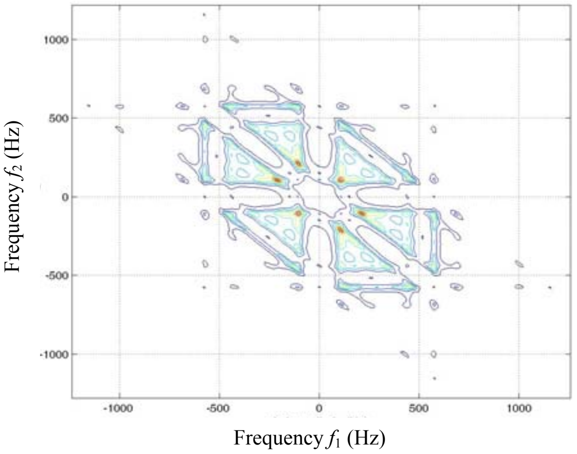

Figure 5. The bispectrum, position 1, driving in the opposite course

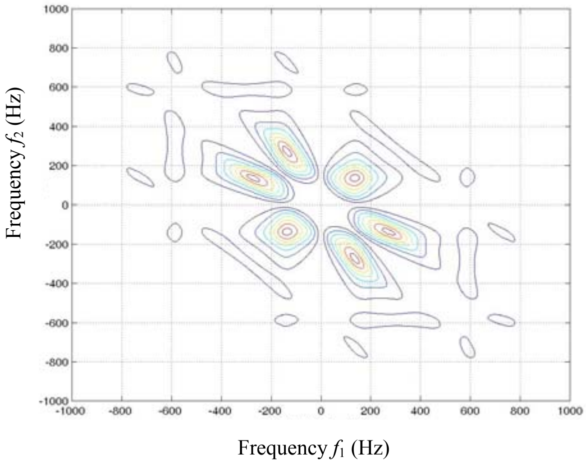

Figure 6. The bispectrum, position 2, driving in the opposite course

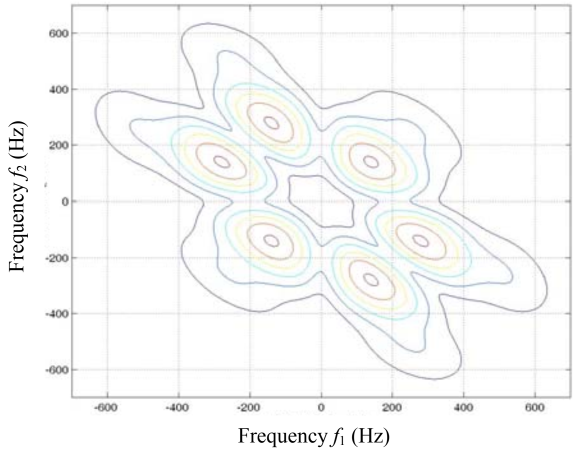

Figure 7. The bispectrum, position 3, driving in the opposite course

Figs. 9 and 10 show an evident connection between the spectrum of the signal and its bispectrum. It is evident that the nature of the local spectral maximum is not the same. In order to clearly determine the origin of the local maximums in the spectrum, it is necessary to correlate hydroacoustic measurements with simultaneous measurements of vibrations on the ship propulsion aggregates and with measurements on the ship hull. Additional vibration measurements and their correlation with the results of the bispectral analysis of HA signals will enable to predict contribution of particular ship aggregates in whole noise and to make distinction among various physical processes. The process of detection and identification of navigable objects will be thus performed with greater probability.

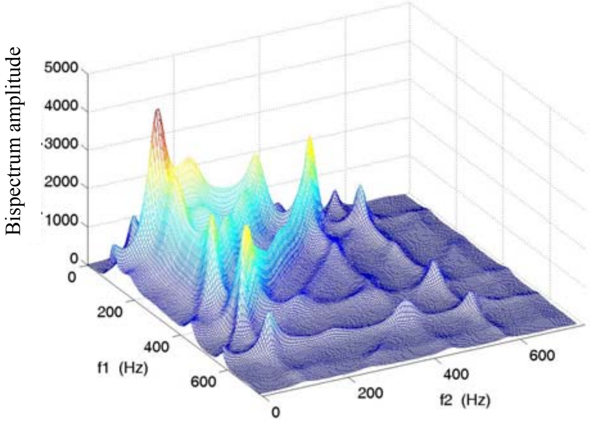

Figure 8. 3-D bispectrum, position 1, driving in the course

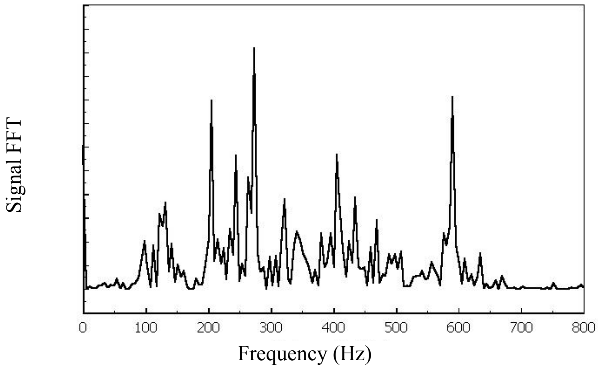

Figure 9. The spectrum of the HA signal, position 2, driving in the course

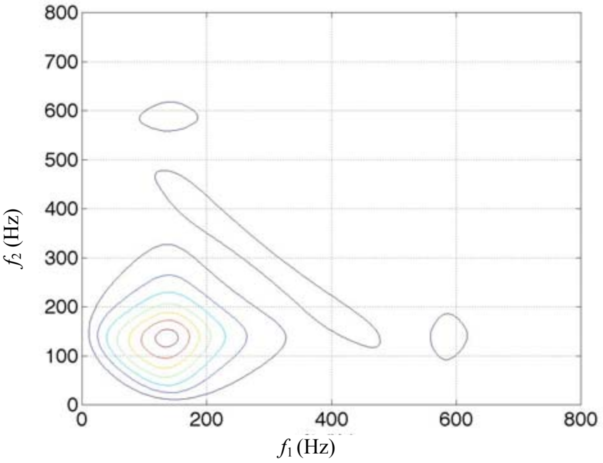

Figure 10. The bispectrum, position 2, driving in the course

Conclusion

The bispectrum analysis of HA signals generated during the ship activity proved its quality in solving problems of detection and identification of navigable objects. In order to improve the process of ship identification as well as the processes and systems which predominately contribute to the radiated HA noise, it is necessary to conduct additional simultaneous vibration measurements at selected points of the navigable object. In this way the image of the navigable object as a source of HA noise will be better known and the results of the bispectrum analysis of radiated noise will enable the application of results of the bispectrum analysis with higher probability.

In addition to detection and identification, the importance of these analyses is in their possible application in diagnostics of proper functioning of the ship propulsion aggregates as well as the ship as a whole. This testing is possible to do without great limitations, at specially selected positions at sea. These positions are acceptable with respect to their ambient noise characteristics and underwater sound propagation.

Similar methods are possible to be applied in a other cases. For example, it is possible to identify vehicles or airplanes on the basis of their noise.

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Bispektralna analiza izračenog šuma plovnih objekata

Pasivna hidroakustička detekcija plovnih objekata podrazumeva mogućnost uskopojasnog frekvencijskog razdvajanja komponenti spektra hidroakustičkog šuma koji nastaje tokom rada različitih agregata plovnog objekta, kao i odvijanja različitih fizičkih procesa tokom kretanja plovnog objekta kroz vodenu sredinu. Najznačajniju ulogu u stvaranju šuma imaju glavni i pomoćni motori, elisa, pumpe, ali i drugi procesi. Da bi se ostvarila detekcija plovnih objekata neophodno je primeniti tehnike bispektralne analize hidroakustičkih signala koje registrujemo u vodenoj sredini tokom kretanja plovnog objekta. U radu je dat prikaz rezultata bispektralne analize prolazne hidroakustičke karakteristike plovnog objekta.

***Ključne reči*: hidroakustička identifikacija, hidroakustički šum plovnog objekta, bispektar, plovni objekat.**

Analyse bispectrale du bruit des objets navigables

La détection hydroacoustique passive des objets navigables signifie la possibilité de séparer, à bandes étroites de fréquence, les composants du spectre de bruit hydroacoustique provoqué par les agrégats divers et les processus pendant le mouvement des objets dans l'eau. Les moteurs principaux et auxiliaires, l'hélice et les pompes ont un rôle le plus important. Afin de réaliser la détection des objets navigables, il est nécessaire d'utiliser les techniques de l'analyse bispectrale des signaux hydroacoustiques enrégistrés dans l'eau. Les résultats de l'analyse bispectrale des caractéristiques hydroacoustiques du passage des objets navigable sont présentés.

***Mots-clés*: identification hydroacoustioque, bruit hydroacoustique de l'objet navigable, bispectre, objet navigable.**