VIBRATION OF THE VESSEL AND BISPECTRUM OF HYDROACOUSTIC NOISE

UDC 534.87

Miodrag Vračar[1], Nenad Kovačević[2]

[1]Military Technical Institute, Ratka Resanovića 111030 Belgrade, Serbia
[2]University Crenfield, College Road, Cranfield, England

Abstract. *The origin of vessels vibrations is dominantly determined by vessels propulsion system, auxiliary systems, pumps, breaking of the waves at the ship hull, etc. All of these systems contribute to the appearance of the underwater sound in water environment. As a source of underwater sound, vessels has the characteristic of directivity. Vibration of the vessel's structure is analyzed using spectra, but hydroacoustic signals are analyzed using spectra and higher order spectral analysis - bispectra. The measuring of the radiated hydroacoustic noise was done simultaneously with multi channel measurements of the vessels vibrations at few characteristics positions of the vessel.*

Key words: *hydroacoustic noise of the vessel, vibrations, spectrum, bispectrum*

INTRODUCTION

The topic hydro acoustic field of vessels has long been an important subject of research in the navies worldwide. Today, at the beginning of the second century of research in this field and its application in various naval combat systems, this assertion is still valid. Knowing the parameters of hydro acoustic signals is of particular importance when the goal is detection and identification of the vessel on the basis of its radiated hydroacoustic noise. Namely, the information about vessel's characteristics is contained in the signal mixed with noise of the water environment. Radiated acoustic noise of the vessels enables its identification and location by using various algorithms. All of those algorithms are based on spectrum and other statistical methods of signal analysis. Hence the importance of underwater signatures of the vessels. Hydroacoustic signatures are most important in the case of military vessels. The main aim is to make vessel's activities quite as much as possible. Noise ranging is performed after major maintenance work, modification, or installation of new equipment in order to reveal any changes of acoustic signature of the vessel. In addition, acoustic signatures of the new vessels are measured to confirm 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 static and dynamic ranging of the vessels is carried out. Dynamic ranging is done when the vessel flow in particular course with constant velocity and measuring of the radiated hydroacoustic noise is performed with one or few hydrophones located at the bottom.

EXPERIMENT

Simultaneous measurements of the vessel vibrations and radiated hydroacoustic noise are planed to be done in the river water environment. The measurements of the vessel vibrations were multichannel, but measuring of the radiated hydroacoustic noise was single channel. Five measuring positions for vibration measurements have been selected (see Table 1). Some of the measuring positions were covered with three axial accelerometers, which enabled collecting vibration data in three dimensions. Hydrophone, piezoelectric transducer, which converts pressure fluctuations of the water environment in wide frequency range (starting from dc levels to 120 kHz) into electrical signal, was used for hydroacoustic measurements of the radiated vessel's noise. The hydrophone was mounted on a special holder, and placed at the river bottom. The river bottom was combination of sand, mud and clay. During experiments, the vessel was moving at constant speed in set course. In all cases, the speed of the vessel was about 10 knots.

SYSTEM FOR VIBRATION MEASUREMENT AND ANALYSIS

Vibrations of the vessel are analyzed using Fast Fourier Transform (FFT) algorithm in two frequency bands, the first from 0 to 100 Hz, and the second from 0 to 800 Hz. In order to enable the moving of the vessel at constant speed, it was necessary to keep the revolving speed of the motor at constant level of about 1200 revolutions per minute downstream, and about 1300 revolutions per minute upstream. Taking into account the overall linear dimensions of the vessel, low frequency range of the vibrations is of particular interest, and therefore the limits of the above frequency bands are defined. Particular interest is in the low frequency band, which is defined from zero to 100 Hz.

Vibrations - acceleration were measured during the movement of the vessel in the measuring points defined in Table 1. Selected measuring positions are representative, and enable the conducting of two types of analysis. The first one is the analysis of its impact on crew. The second is the analysis of distribution of the vibrating modes along the vessel structure.

Table 1. Disposition of the vibration measurement points

No.	Measuring positions and results
1.	Stern (Figs. 7, 8 and 9)
2.	Bearing of the motor shaft (right) (Figs. 12, 13, and 14)
3.	Deck (Fig. 10)
4.	Bow (Figs. 4, 5 and 6)
5.	Drawing - room (Fig. 11)

Used designations of the relevant directions:
x - axis: along axis of the vessel (bow - stern),
y - axis: side axis of the vessel, plus direction is right and
z - axis: vertical axis of the vessel, plus direction is up.

As acquisition and analyzing platform for vibration measurements, B&K PULSE 3560D system was used. The analyses were performed simultaneously with measurements using FFT and CPB software modules. Vibration analysis is possible by using several analyzers and multiple frequency spans simultaneously. Two six-channel modules, type B&K 3032, were used as inputs into PULSE system environment (see Figure 1). The recorded signals were analyzed immediately in octave and one-third octave frequency bands. In this way all measuring places and every measuring cycle are covered. PULSE LabShop software was used to manage the measuring and analysis process.

In addition, the measured data can be exported into different software environments in order to perform the same or additional analysis.
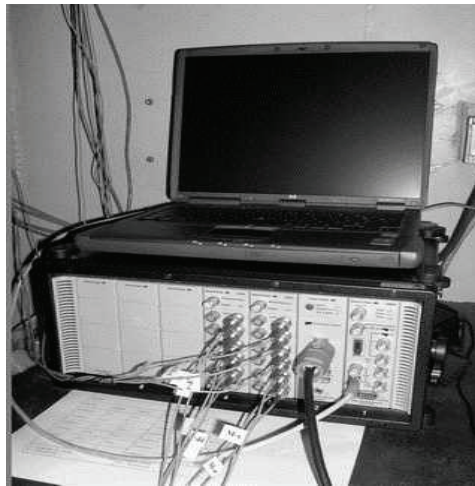

Fig. 1. Analyzer B&K PULSE 3560D

The accelerometer type B&K DeltaTron 4507 B. Fig. 2 was used for the measurement of vibration motion of the vessel structure. The measuring range of the accelerometers was set up before the measuring process started according to the expected values of the acceleration.

Fig. 2. Accelerometer B&K DeltaTron, type 4507 B

The analysis of the measured data was performed using two FFT analyzers. The first one was with frequency range up to 100 Hz with ten averages, and the second in frequency range up to 800 Hz with fifty averages. An example of the setup window is shown in Fig. 3.
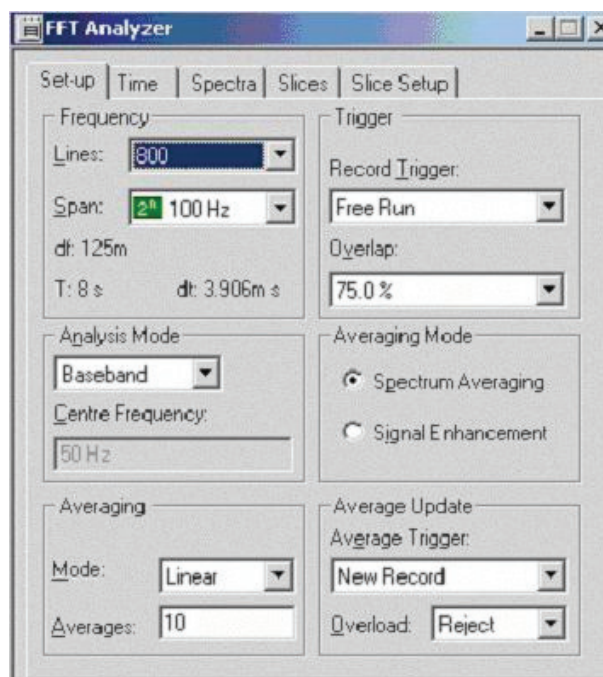

Fig. 3. Setup of FFT analyzer in frequency range up to 100 Hz

A high pass filter was used, with HPF=0.7 Hz, at the output of B&K DeltaTron accelerometers. The PULSE system enables, according to the sampling frequency, anti-aliasing filtration of the signals, too. The sampling rate of the FFT analyzer was 256 Hz, time duration of the sampled signal was 8 s. The Hanning window was used in the calculation of the vibration spectra. The calculation of the vibration spectra was at the resolution of 0.125 Hz, the frequency range from 0 to 100 Hz.

The resulting vibrating spectra are presented as dependence of acceleration, a_{RMS}, (RMS - Root Mean Square), in m/s^2 unit, of frequency in hertz. For the estimation of the impact of the measured data on the vessel's crew, ISO standards are used, such as ISO 2631-1, ISO 6954 and some norms of the former USSR.

The spectra of vibrations analyzed according to the previous procedures are presented in Figs. 4 - 14. The number of revolutions per minute of the main motors was 1290.
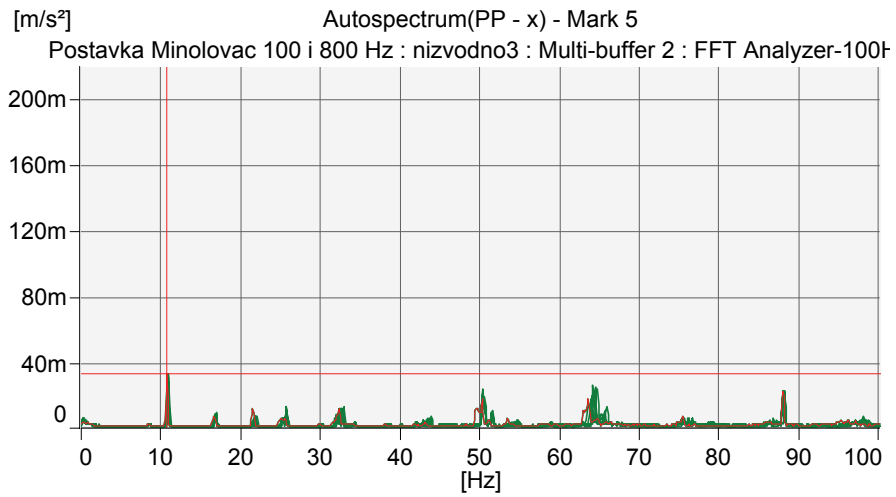
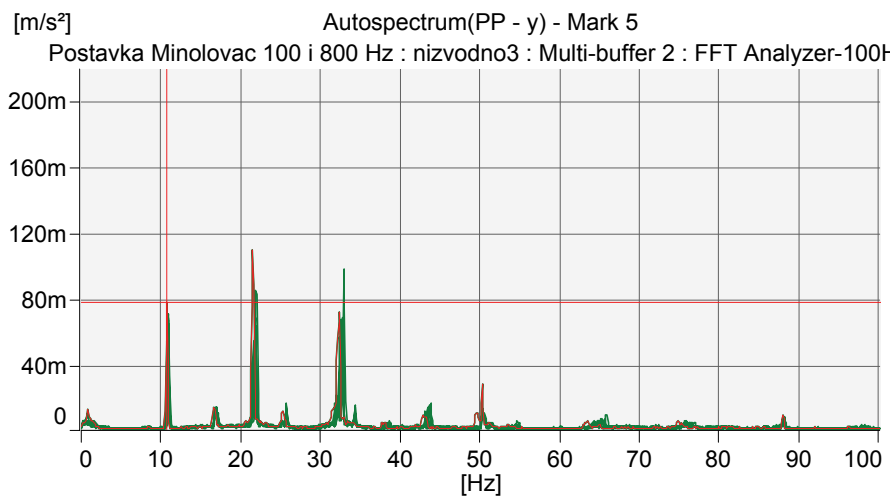Fig. 4. Measuring place vessel bow: all spectra are in direction of x - axis

Fig. 5. Measuring position vessel bow: all spectra are in direction of y-axis
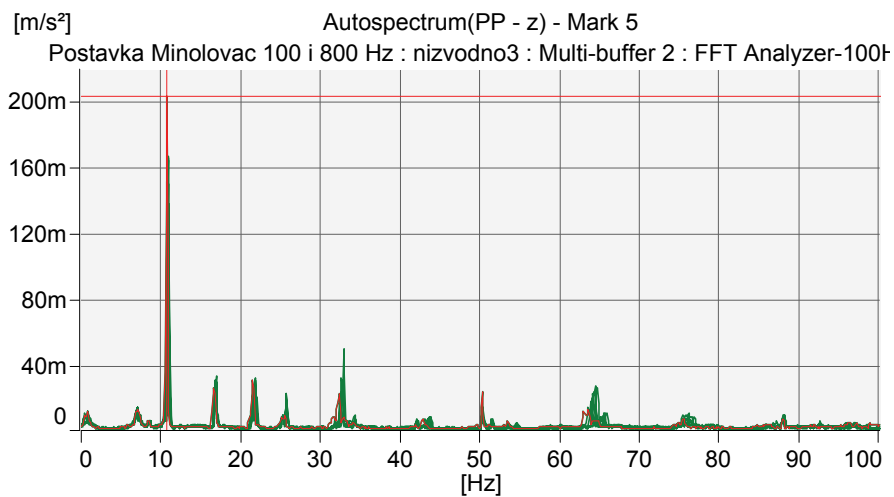
Fig. 6. Measuring position vessel bow: all spectrum are in direction of z-axis
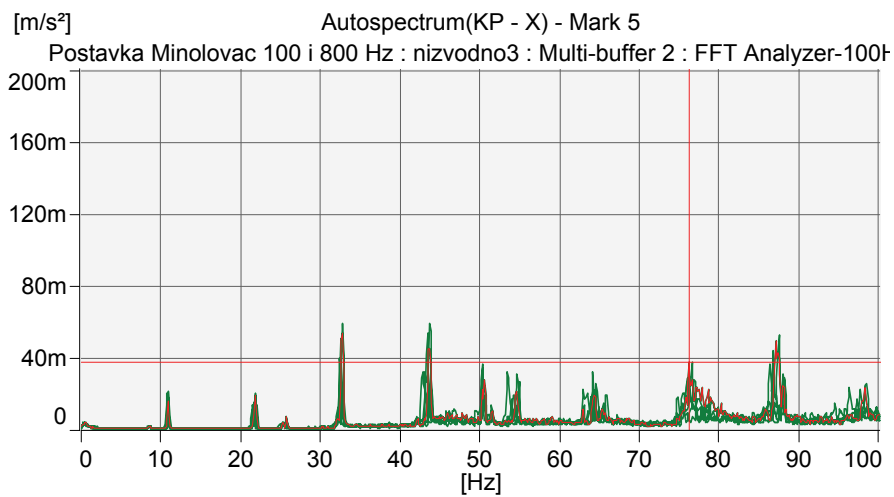

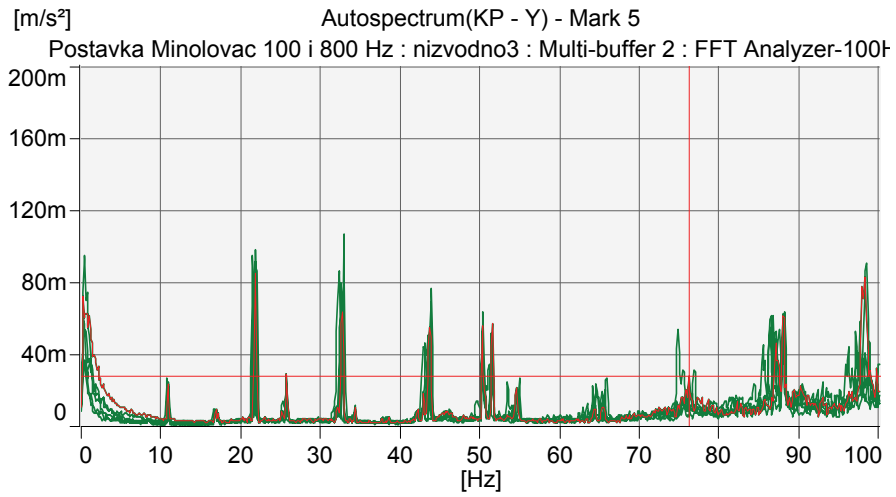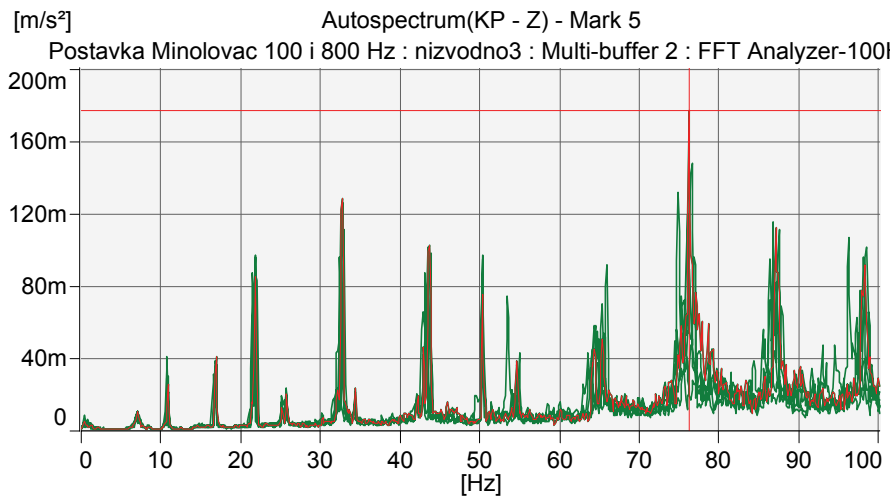Fig. 7. Measuring position at stern: all spectra is in direction of x-axis

[m/s²]   Autospectrum(KP - Y) - Mark 5
          Postavka Minolovac 100 i 800 Hz : nizvodno3 : Multi-buffer 2 : FFT Analyzer-100H

Fig. 8. Measuring position at stern: all spectra are in direction of y-axis

[m/s²]   Autospectrum(KP - Z) - Mark 5
          Postavka Minolovac 100 i 800 Hz : nizvodno3 : Multi-buffer 2 : FFT Analyzer-100H

Fig. 9. Measuring position at stern: all spectra are in direction of z-axis

[m/s²]   Autospectrum(N - Z) - Mark 5
        Postavka Minolovac 100 i 800 Hz : nizvodno3 : Multi-buffer 2 : FFT Analyzer-100H

Fig. 10. Measuring position at deck: all spectra are in direction of z-axis

[m/s²]   Autospectrum(S - z) - Mark 5
        Postavka Minolovac 100 i 800 Hz : nizvodno3 : Multi-buffer 2 : FFT Analyzer-100H
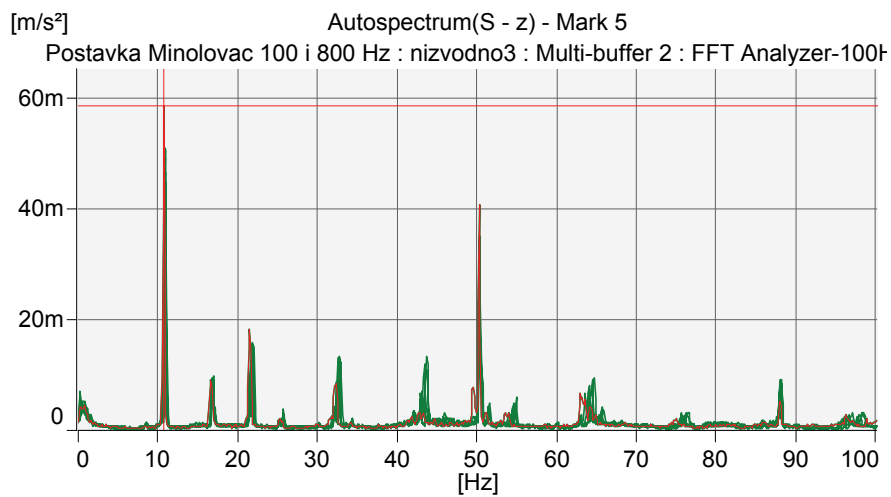
Fig. 11. Measuring position at drawing room: all spectra are in direction of z-axis

[m/s²]   Autospectrum(M -x) - Mark 5
          Postavka Minolovac 100 i 800 Hz : nizvodno3 : Multi-buffer 2 : FFT Analyzer-100H

Fig. 12. Measuring position at right motor: all spectra are in direction of x-axis

[m/s²]   Autospectrum(M - y) - Mark 5
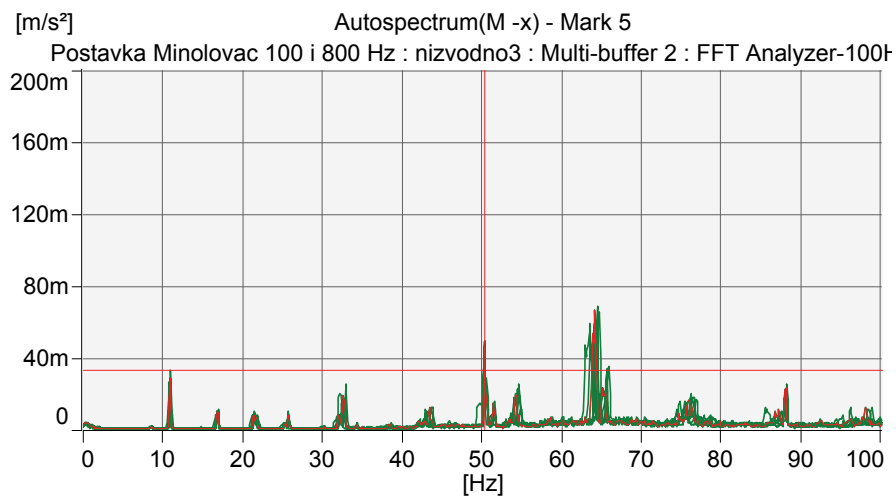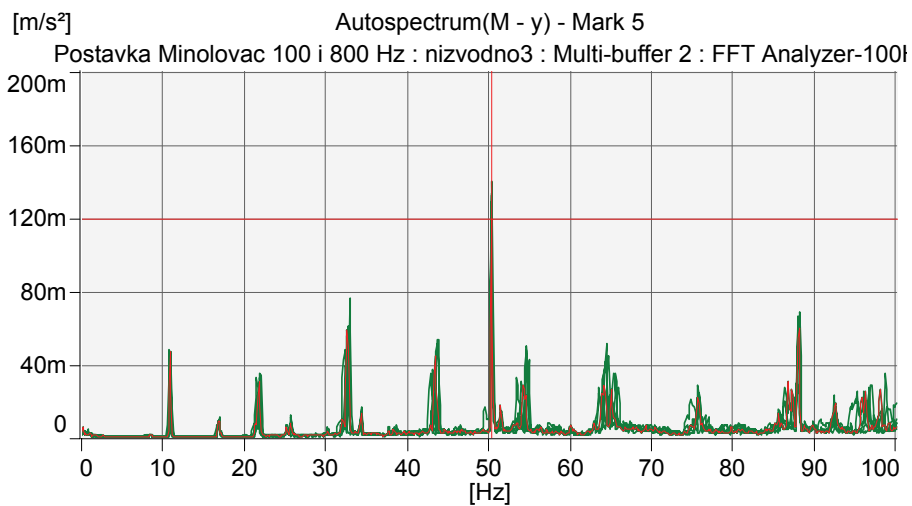   Postavka Minolovac 100 i 800 Hz : nizvodno3 : Multi-buffer 2 : FFT Analyzer-100H

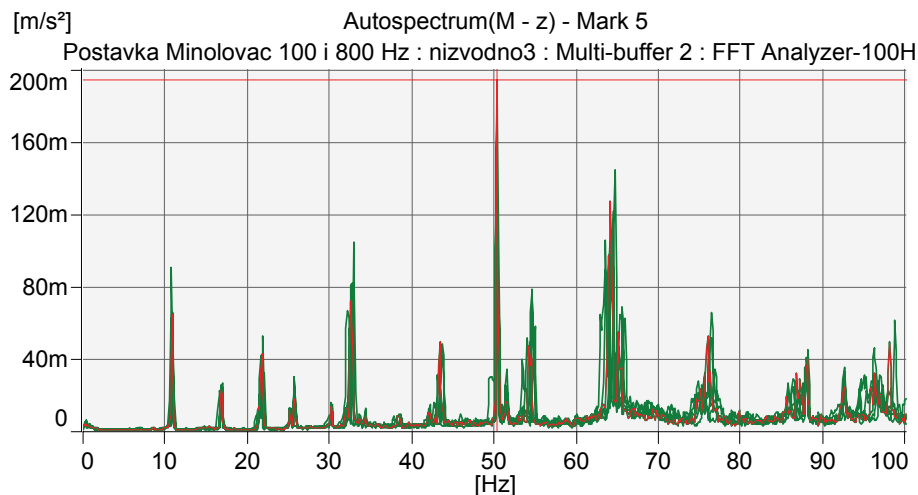Fig. 13. Measuring position at right motor: all spectra are in direction off y-axis

Fig. 14. Measuring position at right motor: all spectra are in direction of z-axis

ORIGIN AND CHARACTERISTICS OF HYDROACOUSTIC NOISE OF THE VESSEL

The main sources of radiated hydroacoustic noise include:

− propulsion system, which include the engine, reduction gears (if any), drive shaft, bearings and other;

− propeller, although a part of the propulsion system, contributes quite differently to the generation of hydroacoustic signals, namely, noise is the result of cavitations produced by the rotating blades;

− auxiliary machinery, such as non-propulsion related mechanical and electrical systems (air conditioning, electrical generators, and pumps) and

− hydrodynamic effects and that include radiated flow noise and flow-induced excitation of plates or other structural features.

Determination of the parameters of electrical signal obtained during the recording of the vessel passing characteristics is an important task when the primary goal is the problem of the vessel identification. Namely, radiated hydroacoustic noise possesses information about vessel's characteristics. As pointed out previously, the most important contribution to the noise characteristics is made by the vessel propulsion system, which generates significant vibrations of the whole vessel structure. So generated vibrations of the vessel structure cause forced vibrations of the hull plates, and these vibrations are transformed into pressure variations of water environment that propagates significant ranges.

Radiated hydoacoustic noise of the vessel into the water environment was recorded using a sensitive pressure piezoelectric transducer, which transforms hydroacoustic pressure fluctuations into an electrical signal, which is proportional to the pressure fluctuations. A hydrophone, type B&K 8104, was used throughout all measurements of the vessel-radiated noise. The measuring chain, besides the hydrophone, was set up from a conditioning preamplifier, a type recorder and a PC computer that served as acquisition unit. A typical shape of the electrical signal obtained during vessel passing above the hydro-

phone is shown in Fig. 15. Time duration of the recorded signal was about thirty seconds. During that time, the radiated hydroacoustic noise was at a relatively high level, above 100 dB re 1μPa. It is obvious too that there exists an interval of time when the radiated noise is particularly pronounced. That time interval is between the tenth and the twentieth second, when the vessel reaches the closest positions (CPA position) concerning the submerged hydrophone.
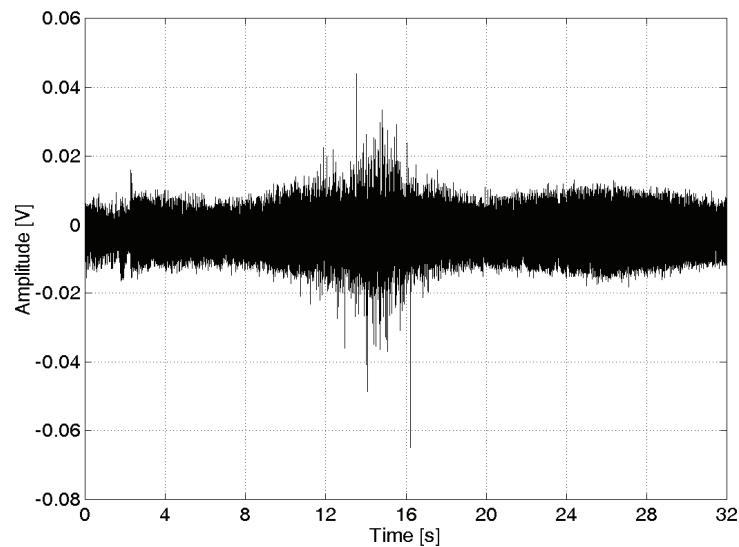

Fig. 15. Time series of the recorded hydroacoustic signal of the vessel, that is proportional to the pressure variations in the water environment

The spectrum analysis of time series from Fig. 15 makes it possible to find out the distribution of hydroacoustic energy in the frequency domain. In addition, the spectral analysis has been a significant tool in the statistical analysis of stationary time series since the late 1940's, when a few researchers from the USA and England proposed a technique of spectral analysis in essentially its present form. The spectrum is only the simplest, and most unusual, of a sequence of moment decompositions for one or more time series [1].

The pressure spectrum of the radiated hydroacoustic vessel noise is calculated when the vessel is at CPA position (see Fig. 16). In low frequency range, up to 300 Hz, there are several emphasized local peaks marked with numbers 1, 2, 3 and 4. The reference value of the pressure spectra of 1 μPa is commonly used in hydroacoustic. Local peaks in the spectra are approximately at frequencies 11, 22, 33 and 50 Hz. The absolute maximum of the pressure spectra is at 50 Hz.
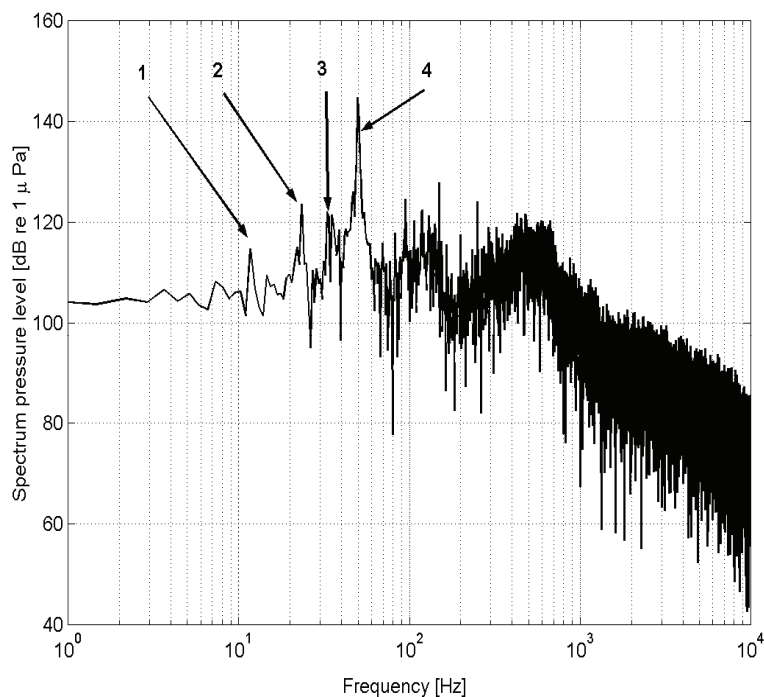
Fig. 16. Pressure spectrum of the radiated hydroacoustic noise in CPA position of the vessel

Classical spectral estimation implies the need for the windowing of the analyzed signal. That means that all unobserved samples are effectively zero, whether or not this is true. The transformation of the observed finite sequence is a distorted version of the infinite sequence transform. Many discrete time windows exist as rectangle (uniform), triangle (Bartlett), raised cosine (Hamming), weighted cosines, and others. The frequency response of the rectangular window has the narrowest main lobe among the windows that have been mentioned. The strategy for window selection is dictated by a trade-off between bias due to interferes in nearby side lobes versus bias due to interferences in distant side lobes [2].

To get a better insight into pressure spectrum variations during all observed time (0 to 30 seconds) some kind of a spectrogram was done (see Fig. 17).
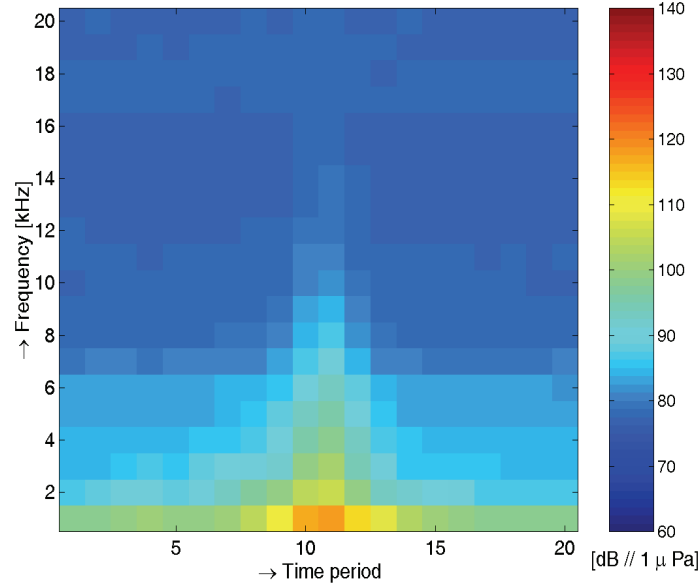
Fig. 17. Spectrogram of the time series from Fig. 15, as illustration of the pressure spectra variation during moving of the vessel in defined course

The spectrogram in Fig. 17 is obtained using the averages in time and frequency domains. Namely, the period around the CPA point is divided into twenty equal time intervals and the frequency range is divided in the same way, too. In such a way a spectrum matrix with dimension 20 x 20 is obtained. The spectrum pressure level of each matrix element is calculated by averaging in time and frequency domain within limits of the previous defined intervals. Discrete Fourier analysis was applied on signals blocks of the length of 4096 points in 4096 points, with overlap of 50%. Sampling rate of the hydroacoustic signal from Fig. 15 was 48.000 Hz.

On the basis of the spectral analysis of the radiated hydroacoustic noise of the vessel it is possible to conclude that there are some local peaks, their intensities and frequency. Unfortunately, it is not possible to conclude if there is a mutual correlation between them.

HIGHER ORDER SPECTRA

Higher order spectra are defined as Fourier transform of the corresponding cumulant sequence. Cumulants of a stationary process are introduced by definitions [3]. The first order cumulant of a stationary process is the mean. The higher order cumulants (the second and the third) are invariant to a shift of mean and are given by following equations:

$$C_{2x}(k) = E\{x^*(n)x(n+k)\}$$
$$C_{3x}(k,l) = E\{x^*(n)x(n+k)x(n+l)\}$$

(1)

where $E\{\cdot\}$ denotes the ensemble expectation operator of time series x.

The cumulants of a stationary real-valued process are symmetric in their arguments,

$$C_{2x}(k) = C_{2x}(-k)$$
$$C_{3x}(k,l) = C_{3x}(l,k) = C_{3x}(-k,l-k). \tag{2}$$

Polyspectrum is defined as Fourier transform of the corresponding cumulant sequence,

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

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

which are the power spectrum and the bispectrum, respectively. The bispectrum is the function of two frequencies and is complex valued.

The bispectrum of a hydroacoustic signal is calculated at three characteristic situations - positions of the vessel relative to the measuring hydrophone. The first one is before the vessel approaches the CPA position, the second when the vessel is at the CPA position and the third when the vessel is moved away from the CPA position. The absolute values of the bispectrums at those three positions are presented as functions of two frequencies (see Figs. 18 - 20). The bispectrums are calculated as two frequency Fourier transform signal blocks of 2048 points and the sampling frequency was 2400 Hz.
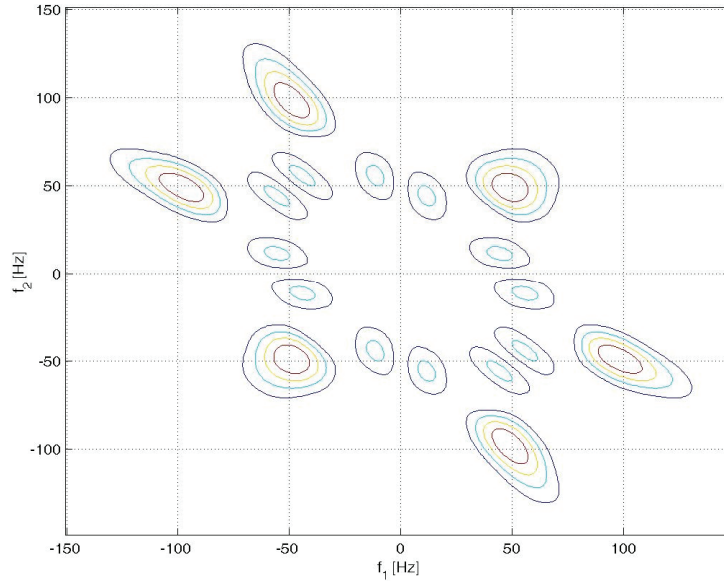

Fig. 18. The bispectrum of hydroacustic signal at the first position when the vessel
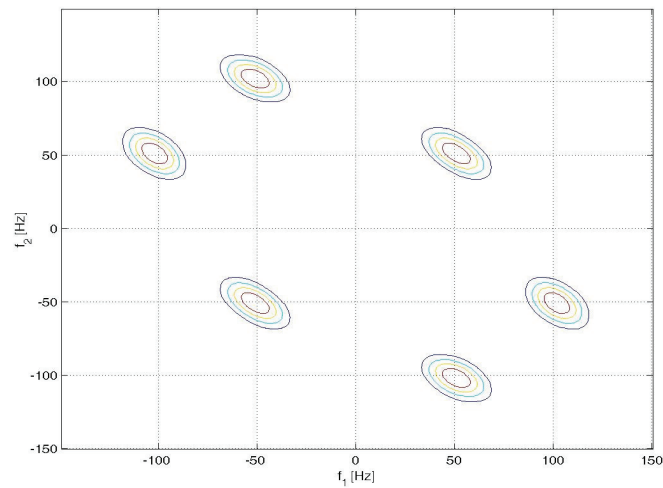   approaches the CPA position. The peaks are at 11 Hz and the maximum at 50 Hz.

Fig. 19. The bispectrum of hydroacustic signal when the vessel is at CPA position. Only one peak is at 50 Hz.

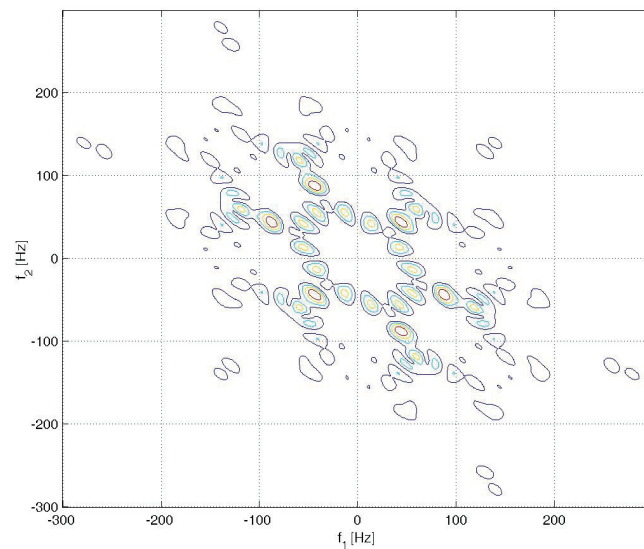

Fig. 20. The bispectrum of hydroacustic signal at the third position when the vessel is moved from the CPA position. The peaks are at 11, 22, 50, 90 and 150 Hz. The most intensive is the peak at 50 Hz.

All peaks, presented at Figs. 18-20, are phase - coupled with the most pronounced peak at the frequency of 50 Hz. At the frequency of 50 Hz the most intensive peak in

vibration spectra is established (see Figs. 13 and 14). Therefore, vibrations of the main motor shaft mostly contribute to the radiated hydroacoustic noise of the vessel. Many authors worked in the field of the application bispectra in solving various problems. Some of the interesting application can be found in references [4-7].

CONCLUSION

The results of measuring vessel vibration suggest that the main motor of the vessel is the biggest generator of vibrations of the vessel structure. The most pronounced vibration component is at 50 Hz. The spectral analysis of radiated hydroacoustic noise of the vessel shows the existence of a few local peaks in low frequency range. The bispectra analysis discovered the same and additionally showed how the main vibration mod is connected with other local peaks in the pressure spectra. This result is significant and will be useful in solving the identification problem of the vessel. In addition, on the basis of one channel measurement it is possible to get information about the time when the vessel approaches or goes away from the measuring position.

REFERENCES

1. Bernard Harris: *Spectral Analysis of Time Series,* Procedings of an Advanced Seminar Conducted by the Mathematics Research Center, United States Army and The Statistics Department at the Univeristy of Wisconsin, Madison, October 3-5, 1966.
2. S.L. Marple, *Digital Spectral Analysis with Applications*, Prentice-Hall. Inc., 1987.
3. Statistics Toolbox for Use with MATLAB®, User's Guide Version 2.1, 1999.
4. Shen M., Sun,L.: *The analysis and classification of phonocardiogram based on higher-order spectra*, Proc. IEEE Workshop on Higher-order statistics, Banff, Alta., Canada, 21-23 July, 1997, pp.29-33.
5. Barker R.W., Hinich, M.J.: *Statistical monitoring of rotating machinery by cumulant spectral analysis*, Proc. IEEE Workshop on Higher-order statistics, South Lake Tahoe, CA, USA, 7-9 June, 1993, pp.187-191.
6. Nikias C.L., Raghuver,M.R.: *Bispectrum estimation: A digital signal processing framework*, Proc. IEEE, 1987, Vol.75, No.7, pp.869-891.
7. Fackrell J.W.A., Mclaughlin S., WHITE,P.R.: *Bicoherence estimation using the direct method. Part 1: Theoretical considerations*, Applied Sig. Process., 1995, Vol.3, pp.155-168.
8. Marple S.L.: Digital Spectral Analysis with Applications, Prentice-Hall. Inc., 1987.

VIBRACIJE PLOVNOG OBJEKTA I BISPEKTAR HIDROAKUSTČKOG ŠUMA

Miodrag Vračar, Nenad Kovačević

Vibracije plovnog objekata prouzrokuju, pre svega, njegov propulzioni sistemi, pomoćni sistemi, pumpe, udari talasa o trup i dr. Svi ovi sistemi doprinose pojavi podvodnog šuma u vodenoj sredini. Kao izvor podvodnog šuma, plovni objekat poseduje karakterističnu usmerenost. Vibracije strukture plovnog objekta su analizirane pomoću spektara, ali hidroakustički signali su analizirani pomoću spektara višeg reda – bispektara. Merenja izračenog hidroakustičkog šuma su izvršena istovremeno sa višekanalnim merenjima brodskih vibracija u nekoliko karakterističnih položaja.