International Workshop Navigation and Motion Control — 2019 IOP Publishing
Journal of Physics: Conference Series **1536** (2020) 012005 doi:10.1088/1742-6596/1536/1/012005

Underwater radiated noise model of marine object

V.V. Prokopovich[1] **and A.V. Shafranyuk**[2]

[1]Software engineer, postgraduate, Concern CSRI Elektropribor, JSC, Saint Petersburg, Russia
[2]Head of a group, Candidate of Technical Sciences, Concern CSRI Elektropribor, JSC, St Petersburg, Russia

e-mail: wm.prokopovich@yandex.ru

Abstract. The paper is devoted to the developing a comprehensive model for underwater radiated noise of marine object in order to model and simulate sonar systems. Many works present underwater radiated noise models, but as a rule, they consider either one of the noise components in order to develop algorithms for the corresponding sonar operation mode, or one of the noise sources in order to design ship parts and assemblies. This paper combines several noise models of marine objects considering additional factors that were not taken into account in these models. The obtained comprehensive model is under verification phase, but its application will significantly expand the possibilities for developing and synthesizing classification and tracking algorithms of sonar system

Introduction

The development of a realistic model of underwater radiated noise (URN) model of marine object is an urgent problem for such applications as ship noise monitoring in order to protect marine ecological systems [1], classification of marine objects [2,3] (especially autonomous uninhabited systems), data processing in sonar systems [4], their modeling and simulation [5], and others.

The main URN sources of marine object to be described by such models are

- propeller noise; it is significant that even at low speeds the rotation noise of the propellers and vortex noise are some of the main sources, and when certain speeds are reached (cavitation inception speed), a cavitation effect arises in the vortex water flows and the noise of the propellers becomes dominant;
- hull noise caused by vibrations due to shaft rotation, engine work, auxiliary mechanisms, etc .;
- hydrodynamic flow noises, manifested at high speeds during the formation of the wake as a result of cavitation on hull and propeller;
- other noises.

Traditionally, when developing the algorithms for passive sonar systems, it is customary to consider three components of the URN of a marine object

- the continuous part of the noise power spectra (CPS), determining its level in a wide frequency band;
- discrete components of the noise power spectra (DCS), usually presented in the form of scales (harmonics of the shaft and blade scales), tonal signals of auxiliary mechanisms, etc.;
- narrow-band amplitude modulation of the broadband part of the noise, consisting of shaft-blade modulation arising from cavitation on the propeller, and modulation caused by sea rolling.

Existing models as a rule consider either one of the noise components in order to develop algorithms for the corresponding sonar operation mode, or one of the noise sources in order to design ship parts and assemblies.

The paper is devoted to the developing a comprehensive URN model for a marine object, which combines several of the most modern specified URN models considering additional factors that were not taken into account earlier. Applying the comprehensive URN model in the design of simulation-modeling systems improve the quality of testing and algorithmic software, debugging procedure. Consequently, it improves quality of technical solutions in designed sonar systems and software. Another important area of using improved URN model is the task of secondary data processing in the sonar system such as classification and estimation of the orientation and motion parameters of marine objects.

1. The traditional underwater radiated noise model of a marine object

The URN models for various noise components and sources are described in many works [1, 3, 5-11, 13-16]. Comprehensive URN models are much less common [4, 5]. An example of comprehensive URN model can be represented:

$$U_{URN}(t) = (1 + U_{SBM}(t) + U_{PRM}(t)) \cdot \mathbf{F}^{-1}\left\{\sqrt{S_{CPS}(f)} \cdot w\right\} + U_{DCS}(t)\,; \tag{1}$$

where $U_{URN}(t)$ is URN; $U_{SBM}(t)$ is modulating process, characterizing shaft-blade modulation; $U_{PRM}(t)$ is modulating process, characterizing pitching and rolling modulation; $S_{CPS}(f)$ is CPS of URN; $\mathbf{F}^{-1}\{\ \}$ is inverse Fourier transform operator; $U_{DCS}(t)$ are tonal signals, characterizing DCS of URN; t is time; f is frequency; w is zero-mean gaussian white noise.

As an example, Fig. 1 shows the power spectral density (PSD) of an object noise with discrete components (a) and an amplitude-modulated signal (b).

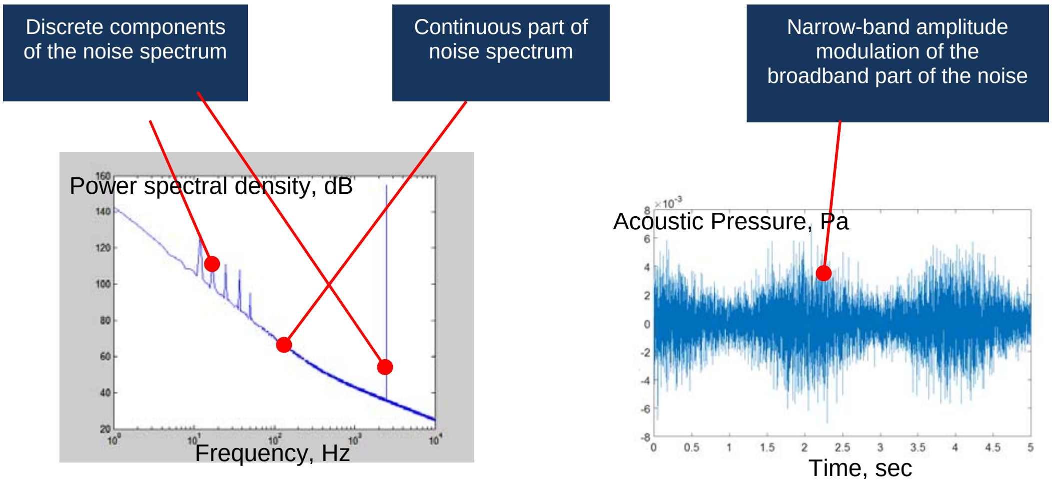

Fig. 1. An example of the underwater radiated noise of a marine object. (a) noise spectrum, (b) modulated signal

The process of blade modulation is described in a simplified form by the following expression [4]:

$$U_{SBM}(t) = \sum_{i=1}^{N_{SBS}} \left(m_i \cdot \cos\left[2\pi \cdot F_{SBM,i} \cdot t + \varphi_{SBM,i} + \delta F_{SBM,i}(t) / F_{SBM,i}\right]\right) \tag{2}$$

where N_{SBS} is a number of harmonics of the shaft-blade scale; m_i is a modulation coefficient of the i-th harmonic; $F_{SBM,i}$ is an average frequency of the i-th harmonic; $\varphi_{SBM,i}$ is an initial phase of modulation corresponding to the *i*-th harmonic; $\delta F_{VLM,i}(t)$ is zero-mean gaussian white noise which defines frequency fluctuations of the *i*-th harmonic.

Pitching and rolling modulation is described by the expression:

$$U_{PRM}(t) = m_P \cdot \cos\left[2\pi \cdot F_P \cdot t + \varphi_P + \delta F_P(t) / F_P\right] + m_R \cdot \cos\left[2\pi \cdot F_R \cdot t + \varphi_R + \delta F_R(t) / F_R\right]; \qquad (3)$$

where m_P, m_R are modulation coefficients of pithing and rolling, respectively; F_P, F_R are average frequencies of pithing and rolling, respectively; φ_P, φ_R are initial phases of modulation corresponding to pitching and rolling, respectively; $\delta F_P(t)$, $\delta F_R(t)$ are zero-mean gaussian white noises which define frequency fluctuations of the pitching and rolling modulation, respectively.

Discrete components of the noise spectrum are described by the expression:

$$U_{DCS}(t) = \sum_{i=1}^{N_{DCS}} \left(a_{DCS,i} \cdot \cos\left[2\pi \cdot F_{DCS,i} \cdot t + \varphi_{DCS,i} + \delta F_{DCS,i}(t) / F_{DCS,i} \right] \right); \qquad (4)$$

with N_{DCS} is total number of tonals in CPS (including various models, which will be discussed below), i is tonal index, $a_{DCS,i}$ is tonal level, $F_{DCS,i}$ is tonal average frequency, $\varphi_{DCS,i}$ is tonal initial phase, $\delta F_{DCS,i}(t)$ is zero-mean gaussian white noise which defines frequency fluctuations of the *i*-th tonal.

It should be noted that the set of tonals in (4) includes both tonals caused by the propulsion and drive shaft [6] and tonals of mechanisms, generators, etc. The last are usually expertly appointed and are beyond the scope work.

The CPS in this model, as a rule, is represented by the Urick model [7] by the expression:

$$S_{CPS}(f) = S_0 - 20 \cdot \log_{10} \frac{f}{f_0}; \qquad (5)$$

where S_0 is normalized to the frequency f_0 (in the band of 1 Hz) PSD level in dB; f_0 – normalizing frequency (usually 1 kHz).

The considered model has a good structure that describes all the main processes of marine object URN. Outside of this approach, only some specific phenomena remain. Nevertheless, taking into account recent URN studies [9-16], it is necessary to improve it in order to increase the adequacy of the model.

2. Proposed underwater radiated noise model of marine object

Recently, a significant number of URN models have appeared that have higher adequacy, which is verified experimentally [8]. The most actual model is the AQUA-project model [9], based on Wittekind-model [10]. In comparison with the Ross [11] and Urick [7] models, which underlie the simulation model considered above, the AQUA model has the following advantages:

- a wider range of frequency response, with lower frequency about 10 Hz. This takes into account the complex shape of the noise spectrum at frequencies band from 10 Hz to 1 kHz, that allows to expand the range of simulation to low-frequency sonar system;
- separation of the CPS noise into three components having different sources. This one allows to take into account the directivity of the noise (with corresponding sources), as well as the influence of amplitude modulation, or its absence.

AQUA-project model defines only CPS noise by the expression [9]:

$$S_{CPS}(f,V) = S_{mach}(f,V) + S_{prop}(f,V) + S_{cav}(f,V) \qquad (6)$$

where V is a speed of the marine object. At the same time, the AQUA-project model suggests, by analogy with Wittekind [10], to divide the noise power spectrum into 3 components, each of which is described as follows.

First is noise of mechanisms

$$S_{mach}(f,V)=P_{base}10^{\frac{K_1+K_2\cdot\log_{10}V}{10}}\text{, for } f<f_{mach}\text{;} \tag{7}$$

$$S_{mach}(f,V)=P_{base}10^{\frac{K_1+K_3\cdot\log_{10}f+K_4\cdot\log_{10}V}{10}}\text{, for } f>f_{mach}\text{,} \tag{8}$$

where P_{base} is power for normalize (Pa^2/Hz), K_1, K_2, K_3, K_4 are coefficients of AQUA-project model, f_{mach} is frequency of mechanisms noise spectrum.

Second is the noise of a non-cavitating propulsion

$$S_{prop}(f,V)=P_{base}10^{\frac{K_5+K_6\cdot\log_{10}f+K_9\cdot\log_{10}V}{10}}\text{, при } f<f_{prop}\text{;} \tag{9}$$

$$S_{prop}(f,V)=P_{base}10^{\frac{K_7+K_8\cdot\log_{10}f+K_9\cdot\log_{10}V}{10}}\text{, при } f>f_{prop}\text{,} \tag{10}$$

where K_5, K_6, K_7, K_8, K_9 are coefficients of AQUA-project model, f_{prop} is frequency of non-cavitating propulsion noise spectrum.

Third is component for cavitation noises, including cavitation of the propulsor and hull

$$S_{cav}(f,V)=P_{base}10^{\frac{K_{10}+K_{11}\cdot\log_{10}f+K_{12}\cdot\log_{10}V}{10}}\text{, при } f<f_{cav}\text{;} \tag{11}$$

$$S_{cav}(f,V)=P_{base}10^{\frac{K_{13}+K_{14}\cdot\log_{10}f+K_{12}\cdot\log_{10}V}{10}}\text{, при } f>f_{cav}\text{,} \tag{12}$$

where K_{10}, K_{11}, K_{12}, K_{13}, K_{14} are coefficients of AQUA-project model, f_{cav} is frequency of cavitation noise spectrum.

Consider the AQUA-project model, similarly to (1), taking into account amplitude modulation and DCS caused by the operation of the propulsion. Firstly, amplitude modulation. According to [12], there are two main (but not exclusively) types of such modulation:

- shaft-blade modulation, caused by the formation of a wake trace from cavitating fluid flows;
- modulation by pitching and rolling, arising from changes in the distance to the water surface from the propeller and leading to power fluctuations due to the Lloyd effect [9].

We formulate several assumptions, which, of course, require experimental verification:

- shaft-blade modulation affects the cavitation noise of the screw, but not the hull. This causes some difficulties using the AQUA model, as it does not separate cavitation noise into the noise of the propeller and the hull. What is certainly advisable to do in the future. Nevertheless, considering the propeller noise predominant, we can consider the noise process with the $S_{cav}(f,V)$ spectrum modulated by the shaft-blade modulation defined by the model [12], which we will consider in more detail below. At the same time, we note that shaft-blade modulation arises only in the cavitation modes of propeller;
- modulation by pitching and rolling affects (taking into account the foregoing) both the CPS component $S_{cav}(f,V)$and $S_{prop}(f,V)$, determined by the noise of the propeller.

Thus, we can reformulate (1) in the form:

$$\begin{aligned}U_{URN}(t,V)&=\left(1+U_{SBM}(t)+U_{PRM}(t,V)\right)\cdot\mathbf{F}^{-1}\left\{S_{prop}\left(f,V\right)+S_{cav}\left(f,V\right)\right\}+\ldots\\&\ldots+\mathbf{F}^{-1}\left\{S_{mach}\left(f,V\right)\right\}+U_{DCS}(t)\end{aligned}\quad, \tag{13}$$

where $U_{PRM}(t,V)=\begin{cases}U_{PRM}(t),V\geq V_{crit}\\0,V<V_{crit}\end{cases}$, V_{crit} is cavitation-inception speed.

Under assumptions made and according to [12], the parameters of the processes that specify the shaft-blade modulation in the form (2) are defied as follows.

$F_{SBM,i+1}=F_{SBM,i}\cdot i$, and $F_{SBM,1}=R\cdot N_{blades}$, where R is rotate per second of propeller, N_{blades} is number of blades.

$\delta F_{SBM,i}(t) = norm(M;\sigma)$, where $M = (3 + 0.25 \cdot W^3) \cdot 10^{-3}$, $\sigma = \max\left[2.5; 2.5 + 5 \cdot (W-2)\right] \cdot 10^{-3}$, W is sea heavy.

$m_1 = norm(0.06; 0.035)$, and the values of the other harmonics ($i > 1$) are not well understood and assigned voluntaristically.

The total number of harmonics in is also unknown and is usually assumed to be 1 ... 2 N_{blades}.

For modulation by pitching and rolling in the same sources, the following recommended choice of parameters is taken from [4].

$F_p = norm(0.12; 0.03)$ $F_R = norm(0.26; 0.05)$;

$\delta F_P(t) = \delta F_R(t) = norm(0.07; 0.02)$;

$m_P = m_R = norm(M_{P,R}; \sigma_{P,R})$, where $M_{P,R} = 0.043 \cdot W$, and $\sigma_{P,R} = norm(0.05, 0.003)$.

For DCS in [6] the following recommendations for parameter values are given: $F_{DCS,i} = R \cdot i$, and the blade frequency $F_{DCS,i} = R \cdot N_{blades} \cdot i$. Those parameters are set in accordance with these recommendations. Other parameters ($\alpha_{DCS,i}$, $\delta F_{DCS,i}(t)$ and N_{DCS}) determined by experts, for example $N_{DCS} = 1 ... 2 \cdot N_{blades}$.

In our note, the source of the blade scale of DCS is propulsion, and the shaft scale is transmitted to the hull and is radiated by it. Thus, the shaft scale, unlike blade scale, is not subjected to modulation due to the Lloyd effect.

For DCS noise from the diesel generator working [13], one can indicate the following frequency of a single tonals and write an expression similar to (4)

$$F_{DG,1} = F_{current} \cdot N_{cyl} / 2 / N_{strokes}$$

where $F_{current}$ is generator current frequency, N_{cyl} is number of cylinders, $N_{strokes}$ is number of strokes.

In addition, in models of noise emission, it is usually practiced to assign other tonals by experts like sum (not a scale), also similar (4). As a result, expression (13) can be reformulating:

$$\begin{gathered} U_{URN}(t,V) = \left(1 + U_{SBM}(t) + U_{PRM}(t,V)\right) \cdot \left(\mathbf{F}^{-1}\left\{S_{prop}(f,V) + S_{cav}(f,V)\right\} + U_S(t)\right) + \ldots \\ \ldots + \mathbf{F}^{-1}\left\{S_{mach}(f,V)\right\} + U_B(t) + U_{DG}(t) + U_{other}(t) \end{gathered} \quad , \quad (14)$$

where $U_S(t)$ are shaft scale tonals; $U_B(t)$ are blade scale tonals; $U_{DG}(t)$ are diesel generator tonals; $U_{other}(t)$ are other tonals, assign by expert.

3. Underwater radiated noise directivity

URN directivity is a rather difficult to model. In some cases, URN directivity can be calculated analytically [14], but more often it can be obtained either by measuring specific marine objects, or in the form of a statistical average value for a certain class of objects. Among the most common models in the literature, we can distinguish noise models of propellers, for example [14-16]. Based on the work [14], when studying a specific propeller in non-cavitation mode, the noise level normal to the propeller is 70 percent of the noise level behind the propeller.

In general, we can only indicate that the directivity of the noise components is different and has both horizontal and vertical components. Denoting by the directivity coefficient of URN power, we finally rewrite (14) in the form:

$$\begin{aligned}
&U_{URN}(t,V)=\left(1+U_{SBM}(t)+U_{PRM}(t,V)\right)\times\ldots\\
&\ldots\times\begin{pmatrix}D_{prop.noncav}(\alpha,\beta)\cdot\left(\mathbf{F}^{-1}\left\{S_{prop}(f,V)\right\}+U_{S.noncav}(t)\right)+\ldots\\ \ldots+D_{prop.cav}(\alpha,\beta)\cdot\left(\mathbf{F}^{-1}\left\{S_{cav}(f,V)\right\}+U_{S.cav}(t)\right)\end{pmatrix}+\ldots\\
&\ldots+D_{hull}(\alpha,\beta)\cdot\left(\mathbf{F}^{-1}\left\{S_{mach}(f,V)\right\}+U_{B}(t)+U_{DG}(t)\right)+D_{other}(\alpha,\beta)\cdot U_{other}(t),
\end{aligned} \tag{15}$$

where $D_{prop.noncav}(\alpha,\beta)$ is directivity coefficient of non-cavitating propulsion noise, $D_{prop.cav}(\alpha,\beta)$ is directivity coefficient of cavitating propulsion noise, $D_{hull}(\alpha,\beta)$ is directivity coefficient of hull noise, $D_{other}(\alpha,\beta)$ is directivity coefficient of other noise, α,β are angle in horizontal and vertical plane, respectively. It should be noted that in (15) the blade scale tonals are divided into two noise $U_{S.noncav}(t)$ and $U_{S.cav}(t)$, since the directivity of propeller noise is different in before $V<V_{crit}$ and after $V\geq V_{crit}$ cavitation modes. That's why $U_{S.noncav}(t)\equiv 0$ for $V\geq V_{crit}$; $U_{S.cav}(t)\equiv 0$ for $V<V_{crit}$.

Conclusion

The paper proposes the author's URN model of marine object, obtained by combining two of the most advanced in its part models, namely AQUA [9], describing the CPS and DCS and amplitude modulation models, describing narrow-band processes in radiation and modulation [12]. At the same time, the authors made some assumptions that allowed them to clarify the model of narrowband components in terms of DCS modulation and noise directivity. The additive nature of the AQUA model also made it possible to represent the direction of the object noise more adequately. Of course, the obtained model needs verification using in-situ data. However, its presence will significantly expand the work on the development and synthesis of algorithms for classification and tracking of marine objects, which play a significant role in automatic systems, which have become widespread in recent years. Nevertheless, it should be noted that in simulation using comprehensive URN model the possibility of use other URN models [1,7] should be considered as well.

The paper was supported by Russian Foundation for Basic Research project no. 19-08-00253 A.

REFERENCES

[1] Wittekind, D. The increasing noise level in the sea—a challenge for ship technology, Proceedings, 104th Congress of the German Society for Maritime Technology, September 29, Hamburg, Germany., 2009.

[2] Moura, Natanael & Seixas, Joao & Ramos, Ricardo. Passive Sonar Signal Detection and Classification Based on Independent Component Analysis. 10.5772/18286, 2011.

[3] Mashoshin A.I., Shafranyuk Y.V. Sintez algoritma avtomaticheskoj klassifikacii celej na osnove analiza amplitudnoj modulyacii ih shumov [Synthesis of an algorithm for automatic classification of targets based on an analysis of the amplitude modulation of their noise], *Fundamental'naya i prikladnaya gidrofizika* [Fundamental and Applied Hydrophysics], 2014. T. 7.

[4] Kebkal K.G., Mashoshin A.I. Acoustic Positoning Methods of Autonomous Underwater Vehicles / Giroskopiya i Navigatsiya. 2016, Vol.24, No. 3 (94), p. 15-130.

[5] A. I. Mashoshin, Optimizaciya ustrojstva obnaruzheniya i izmereniya parametrov amplitudnoj modulyacii podvodnogo shumoizlucheniya morskih sudov [Optimization of the device for detecting and measuring the parameters of the amplitude modulation of underwater noise emission from marine vessels], *Akusticheskij zhurnal* [Acoustic Journal], 2013, V 59, № 3, p. 347–353

[6] Y.V. Shafranyuk, Imitator signalov na vyhode priemnyh elementov passivnoj gidroakusticheskoj stancii s gibkoj protyazhennoj buksiruemoj antennoj [A simulator of

signals at the output of receiving elements of a passive sonar station with a flexible extended towed antenna], *Nauchno-tekhnicheskij vestnik informacionnyh tekhnologij, mekhaniki i optiki* [Scientific and Technical Journal of Information Technologies, Mechanics and Optics], 2012, № 4 (80)

[7] I.M. Rud'ko, Stohasticheskaya model' zvukoryada [Stochastic scale model], *Matematicheskaya teoriya upravleniya. Upravlenie bol'shimi sistemami* [Mathematical control theory. Management of large systems]., Vol 49, 2014 (80)

[8] R. J. Urick. Principles of underwater sound. McGraw-Hill, 1983.

[9] Zilong PENG, Jun FAN, Bin WANG, Analysis and Modelling on Radiated Noise of a Typical Fishing Boat Measured in Shallow Water Inspired by AQUO Project's Model, Archieves of acoustics Vol. 43, No. 2, pp. 263–273 (2018)

[10] Audoly C., Rizzuto E., Ship underwater radiated noise patterns, AQUO European Collaborative Project, Deliverable D2.1., 2015

[11] Wittekind D., A Simple Model for the Underwater Noise Source Level of Ships, Journal of Ship Production and Design, Vol. 30, No. 1, February 2014, pp. 1–8

[12] D. Ross. Mechanics of underwater noise. Peninsula Publishing, 1976.

[13] A.A. Kudryavcev K.P. Luginec, A.I. Mashoshin Ob amplitudnoj modulyacii podvodnogo shuma morskih sudov [On the amplitude modulation of underwater noise of marine vessels.] *Akusticheskij zhurnal* [Acoustic Journal] 2003 Vol 49 T2 p. 224-228

[14] Ignacy Gloza, Stefan Jan Malinowski, Identification of the ship's underwater noise sources in the coastal region/ HYDROACOUSTIC 2001

[15] Kostas Belibassakis, Generation and propagation of underwater noise from marine propellers, Euronoise 2018

[16] B. Mousavi, A. Rahrovi, S. Kheradmand, Numerical simulation of tonal and broadband hydrodynamic noises of noncavitating underwater propeller , 2014

[17] Ji-Sung Jang ; Hyung-Taek Kim ; Won-Ho Joo, Numerical Study on Non-Cavitating Noise of Marine Propeller, Inter-noise 2014