UDC 534.1

DOI: 10.20535/2523-4455.mea.331206

Physical Conditions Limiting the Acoustic Power Radiated by Location Devices

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Abstract **—The article shows that the physical conditions limiting the acoustic power radiated by location devices are the levels of permissible strengths of their elements. The purpose of this paper is to analyze each of these limitations in detail. It is determined by the method of systematic analysis that these strengths include mechanical, electrical and cavitation. Each of them is associated with its own physical field, which takes part in the formation of a given acoustic power of a location device. As a result, the physical reasons for the appearance of electrical, mechanical and cavitation strengths are established. Analytical expressions between the levels of the given strengths and the powers of acoustic radiation are determined.**

Keywords — electrical; mechanical; cavitation strengths; acoustic radiation power; analytical dependencies.

I. Introduction

Any location device is designed to determine the range and spatial coordinates of the sought object. The range equation *r*, which is related to the parameters of the location device, has the form [1, 2]:

$$r^4 10^{0,2\beta r} = W_a K^2 \delta A_i , \qquad (1)$$

where β – the sound attenuation coefficient in an elastic medium, which in general form is determined by the expression $\beta = Bf^b$ (*B* and *b* – constant coefficients, *f* – the frequency of sound radiation); W_a – the radiated acoustic power; *K*– the antenna concentration coefficient of the device; δ – the protection of the device from noise of the receiving path; A_i – a coefficient that takes into account the equivalent radius of the sought object, anomalies of the elastic medium and energy losses of the location device.

Analysis of the range equation (1) shows that the determining factor for increasing the range *r* of a device is its acoustic power W_a. This power is created by the acoustic antenna of this location device through the operation of three physical fields in it – electric, mechanical and acoustic.

In [3] it was shown that the fundamental element of the functioning of acoustic antennas in the processes of energy conversion and its spatial formation is the fulfillment of the conditions of the connection of these fields and processes. This is due to the fact that the functions of energy conversion and its spatial formation, which are the basis of the functioning of acoustic antennas in both radiation and reception modes of location devices, have their own features.

The peculiarities of acoustic antennas in the energy conversion mode are the mutual connection of their electrical, mechanical and acoustic fields [4-6]. In

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the spatial formation of energy, the peculiarity lies in the interaction of the acoustic fields of individual antenna elements, which is due to the multiple process of radiation and reflection of sound waves [7-10]. And, therefore, since acoustic fields are elements of the processes of both conversion and spatial formation of energy, the conditions of connection include, in addition to the two features mentioned above also a feature caused by the interaction between the processes of conversion and formation of energy.

However, the requirements for the energy efficiency of location devices are not limited to these connectivity conditions alone. From the physical conditions, it is clear that each of the physical fields has its own limitations in terms of ensuring the maximum acoustic power radiation by the antenna. These limitations include: for the mechanical field – the mechanical strength of the antenna and its transducers; for the electrical field – the electrical strength of the antenna; for the acoustical field – the cavitation strength of the elastic medium in which the location device operates.

The purpose of this paper is to analyze each of these limitations in detail.

II. Mechanical strength

For use in the construction of antennas of the main operating modes of ship-based location devices, cylindrical and rod oscillatory systems are most widely used. However, rod transducers cannot be used in the construction of ship-based location devices, since their dimensions and mass increase in the cube when the resonant frequency decreases below 3 kHz and become impossible for use both in the manufacture and operation of ship-based location devices. Low-frequency antennas of the main operating modes of ship-based location devices can be built only on circular cylindrical transducers. We will consider them in this paper.

The mechanical strength of acoustic antenna and transducer structures refers to their internal physical factors that limit the ability to radiate acoustic power [11]. In this case, the strength of their structures is determined by the strength of their weakest node. As practice has shown, in acoustic antennas and transducers, when subjected to mechanical loading, such a node is an active element made of piezoceramics [11].

During operation, antenna structures made of transducers are subjected to both static and dynamic or alternating mechanical loads. Static strength determines the property of structures to resist destruction due to rupture under the action of tensile forces caused by external pressure. Its quantitative measure is the maximum tensile stress σ_g that a certain structural material can withstand. For piezoceramic materials, the compressive strength $\sigma_s = (35-50)\cdot 10^3$ N/cm² is an order of magnitude higher than the tensile strength $\sigma_r = (1{,}7-3)\cdot 10^3$ N/cm².

Mechanical dynamic stresses arise during oscillations of the active elements of the antenna and transducers. They are emerged when the antennas operate in the mode of sound energy radiation and are cyclically variable. Their magnitude depends on the characteristics of the radiation mode, the design of the antennas, the nature of the oscillations, the parameters of the electromechanical oscillatory system and the technology of assembling the antennas. Therefore, the greater the acoustic power radiated by the antenna, the greater the mechanical dynamic stresses are emerged in its active element.

In particular, for a cylindrical antenna and transducers operating on longitudinal oscillations, the radiated acoustic power W_a is determined by the expression [12]:

$$W_a = \frac{1}{2}\alpha(\rho c)_p S \cdot v_m^2,$$

where α – is the dimensionless coefficient of the active component of the antenna radiation resistance; $(\rho c)_p$ – is the specific wave resistance of the elastic medium in which the antenna operates; S – is the area of the antenna radiating surface; v_m – is the maximum amplitude of the oscillation velocity.

The relationship between the amplitudes of mechanical stress σ_m and the vibrational velocity v_m in a plane wave propagating along the direction of oscillation of the active element is

$$v_m = \frac{\sigma_m}{(\rho c)_k},$$

where $(\rho c)_k$ is the specific wave resistance of the piezoceramic.

In the general case, the maximum mechanical dynamic stresses σ_{dm} that arise when the acoustic power W_a is radiated at the resonant frequency and this power itself are related by the expression

$$\sigma_{dm} = \left[\frac{2(\rho c)_k^2}{(\rho c)_p}\frac{W_a}{S}B_i^2\right]^{-1/2},$$

where B_i is the coefficient determined by the shape of the oscillations [12].

Thus, the increase in the amount of acoustic power radiated by the location device is limited from the side of the mechanical field of the antenna by such a dynamic characteristic of this field as mechanical strength. This strength, which describes the mechanical dynamic

DOI: 10.20535/2523-4455.mea.331206

stresses emerged in the antenna by the energy radiation mode, depends on the level of this energy, the area of the radiating surface, the specific wave impedance of the piezoceramics used in the antenna, the degree of acoustic loading of the antenna and the forms of oscillations used in the construction of the antenna.

III. Electrical strength

Electrical strength is the second internal factor limiting the increase in the energy capacity of location devices. The problem is exacerbated by the fact that powerful electric fields, which provide radiation of acoustic powers, are created in antenna designs whose elements operate in liquid media.

The physical reasons for the decrease in the electrical strength of location devices are:

- destruction of structural insulation units in antennas as a result of partial electric discharges;
- natural aging of structural electrical insulating materials;
- deterioration of the electrical parameters of antenna elements due to wetting of the insulation of their active elements.

For piezoceramic antennas, the electrical strength is determined by the properties of the piezoceramic. This is confirmed by the following expression for a circular cylindrical antenna:

$$W_a = \left[\frac{k_{33}^2}{\left(1-k_{33}^2\right)}\right] Q_m \omega_p C_0 U^2 \eta_{am} ,$$

where W_a – acoustic radiation power; k_{33} – electromechanical coupling coefficient of the applied piezoceramics; Q_m – mechanical Q-factor of the antennas; ω_p – resonant frequency of the mechanical oscillatory system of the antenna; C_0 – static capacitance of the piezoceramic element of the antenna; U – electrical excitation voltage of the antenna; η_{am} – acoustic-mechanical coefficient of its energy conversion efficiency.

To radiate acoustic power W_a at the resonance frequency ω_p, it is necessary to apply an electric voltage U to the antenna. Its amplitude value is determined by the expression

$$U = \left[\frac{2W_a r_s}{n^2 \eta_{am}^2}\right]^{1/2} .$$

Here r_s is the acoustic radiation resistance of the antenna; n is the coefficient of its electro–mechanical transformation.

During the operation of antennas, moisture gradually penetrates through the moisture-proof shell of their transducers and is absorbed by the entire volume of their electrical insulation materials. This absorption is proportional to the moisture solubility coefficient of the material. When the insulation is moistened more than a certain critical value, there is a sharp drop in the electrical strength of the insulation. It is due to the formation of a film on the surface of the piezoelectric elements of the transducers or the occurrence of delamination in the solid insulation during their compounding. The water film on the surface of the piezoelectric elements covers the space between their electrodes. The electrical strength of the solid insulation of the transducers is determined by the increase in its dielectric losses $\mathrm{tg}\delta$ depending on the increase in moisture content C. This dependence is determined by the expression $\mathrm{tg}\delta = 10AC^2 + B$, where A and B are constant values. The specified electric voltage U corresponds to its critical value $\mathrm{tg}\delta_{cr}$, at which the insulation breakdown occurs. The higher the voltage U, the lower, other things being equal, the value of $\mathrm{tg}\delta_{cr}$. Accordingly, the lower the allowable critical moisture content of the insulation C_{cr}.

Thus, determining the electrical strength of antenna and transducer designs is related to knowledge of the characteristics of electrical insulating materials.

The main task of insulation is to meet certain requirements for the electrical resistance of transducers R_{el}. This resistance consists of three parallel-con–nected resistances: the resistance of electrical losses of the piezoelectric ceramic element of the transducer $R_{el.l}$; the resistance of electrical losses $R_{el.i}$ in the elements of electrical insulation and sealing; the resistance of the active piezoelectric ceramic element and the elements of electrical insulation to direct current $R_{el.c}$. The first of them is determined by the expression $R_{el.l} = \dfrac{1}{\omega C_n \mathrm{tg}\delta_n}$, where C_n and $\mathrm{tg}\delta_n$ are the capacitance and the tangent of the dielectric loss angle of the piezoelectric element. The second resistance $R_{el.i}$ is $R_{el.i} = \dfrac{1}{\omega C_i \mathrm{tg}\delta_i}$, where the capacitance C_i and the tangent of the dielectric loss angle $\mathrm{tg}\delta_i$ are created by the elements of electrical insulation and sealing. The resistance of the active element and the elements of electrical insulation to direct current is $R_{el.c} = \dfrac{\rho_i l_i}{S_i}$, where ρ_i, l_i, S_i are the specific electrical resistance of the material, the length and cross-sectional area of the *i*-th element of the transducer. The values of all

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the components given in the formulas can be found in [11, 12].

IV. Cavitation strength of the working environment

The third physical factor that limits the increase in acoustic power radiated by a location device when it operates in a liquid is the cavitation strength of the elastic medium. The cavitation strength of the medium refers to an external physical factor limiting the increase in radiated acoustic power.

The phenomenon of cavitation is that in liquids, under high tensile forces, forces arise that exceed the forces of adhesion between their particles. This causes local ruptures of liquids with the formation of voids – cavities, which are filled with air and vapor dissolved in liquids. Then these cavities close, accompanied by the appearance of various effects (microshock waves of spherical type, directed microflows, etc.). One of the physical causes of cavitation is the creation of an acoustic field in liquids. In it, during the half- periods of rarefaction, cavitation bubbles arise, which suddenly close after the transition of the sound wave to the region of increased pressure.

The mixture of liquid with cavity bubbles significantly affects the possibilities of increasing the acoustic power radiated by the antenna. The physical reasons for this are as follows.

First, the layer of liquid saturated with cavitation bubbles, which is in contact with the radiating surfaces of the antenna and its transducers, is physically close to an acoustically soft screen. This is due to the decrease in the wave resistance of the mixture of liquid with bubbles. Therefore, this layer prevents the radiation of acoustic energy into the surrounding environment. This causes a decrease in the acoustic pressure in the sound field. In the absence of cavitation, an increase in the electric voltage that excites the antenna is the cause of an increase in the radiated acoustic energy. The appearance of cavitation phenomena slows down this increase, and a further increase in the electric energy supplied from the location device to its antenna is not accompanied by an increase in the radiation power. Moreover, with significant cavitation, this power may even decrease, since its losses due to absorption and scattering of sound waves by cavitation bubbles appear.

Secondly, the decrease in the wave resistance of the working medium, which is caused by cavitation, sharply increases the amplitude of oscillations of the radiating surface of the antenna and disrupts its operation. This increase in the amplitude of oscillations causes an increase in mechanical stresses in the active element of the antenna, which can lead to its destruction. In addition, with strong cavitation, the collapse of bubbles near the radiating surfaces of the antenna and its transducers causes the appearance of microexplosions. Their presence is the cause of mechanical destruction (erosion) of the radiating surfaces of the antenna and its transducers.

The listed causes and consequences of antenna operation in cavitation conditions encourage us to look for ways to prevent its occurrence. The most important of these possibilities is to limit the radiation power to values corresponding to the cavitation threshold. This threshold is determined by the level of specific acoustic power $W_p = \frac{W_a}{S}$, where W_a is the radiated acoustic power, S is the area of the radiating surface. It depends on the parameters of the working environment (the depth of the antenna, temperature, gas content, etc.) and the antenna parameters (the frequency of sound radiation, the duration of the radiated pulses, their duty cycle, the unevenness of the oscillation speed and acoustic pressure on the radiation surface of the antenna and transducers, etc.). The dependence of the cavitation threshold on the depth of immersion h of the antenna during continuous radiation has the form $W_p = 0{,}3(1+0{,}1h)^2$, where h is determined in meters.

Thus, for antennas of location devices operating in liquid environments, the limitation of radiated power is determined by the expression $W_a = W_p S$.

Conclusions

It has been established that, in addition to the conditions of coherence, the second physical factor that limits the acoustic power of sound radiation by location devices is the presence of a number of physical factors. Each of them is associated with those physical fields that interact in the conditions of coherence with each other in acoustic antennas, creating the radiation power of the location devices. For an electric field, this is the electrical strength, for a mechanical field – mechanical strength, and for an acoustic field - this is the cavitation strength of the working medium.

The physical reasons for the appearance of each of these limitations have been established. Analytical relations for calculating the levels of mechanical and electrical strengths depending on the acoustic energy radiated by the location device have been determined. This allows for the search for technical ways to increase the level of radiated acoustic energy, while leaving the levels of electrical, mechanical and cavitation strengths acceptable.

DOI: 10.20535/2523-4455.mea.331206

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Надійшла до редакції 29 травня 2025 року
Прийнята до друку 17 листопада 2025 року

УДК 534.1

DOI: 10.20535/2523-4455.mea.331206

Фізичні умови обмеження акустичної потужності, що випромінюється локаційними засобами

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***Анотація*—В наведеній статті показано, що фізичними умовами обмеження акустичної потужності, що випромінюється локаційними засобами, є допустимі рівні міцностей їх елементів. Визначено, що до цих міцностей відносяться механічна, електрична і кавітаційна. Кожна з них пов’язана зі своїм фізичним полем, яке приймає участь у формуванні заданої акустичної потужності локаційного засобу. Кожне з фізичних полів має свої обмеження з точки зору забезпечення випромінювання антеною локаційного засобу максимальної акустичної потужності. До цих обмежень відносяться: для механічного поля – механічна міцність антени локаційного засобу та її перетворювачів; для електричного поля – електрична міцність антени локаційного засобу; для акустичного поля – кавітаційна міцність пружного середовища, в умовах якого працює локаційний засіб.**

В результаті встановлені фізичні причини появи електричної, механічної і кавітаційної міцностей. Визначені аналітичні вирази між рівнями наведених міцностей і потужностями акустичного випромінювання. Встановлено, що крім умов зв’язаності другим фізичним чинником, який обмежує акустичну потужність випромінювання звуку локаційними засобами є наявність ряду фізичних факторів. Кожен з них пов'язаний з тими фізичними полями, які взаємодіють в умовах зв’язаності між собою в акустичних антенах локаційних засобів, створюючи потужність випромінювання локаційного засобу.

Для електричного поля це електрична міцність, для механічного поля – механічна міцність і для акустичного поля – це кавітаційна міцність робочого середовища. Встановлені фізичні причини появи кожного з цих обмежень.

Механічна міцність, що описує механічні динамічні напруження, що створюються в антені режимом випромінювання енергії, залежать від рівня цієї енергії, площі випромінюючої поверхні, питомого хвильового опору застосованої в антені п’єзокераміки, міри акустичного навантаження антени та форми коливань, що використовуються при побудові антени.

Електрична міцність локаційних засобів залежить від руйнування вузлів ізоляції конструкцій в антенах в результаті дії часткових електричних розрядів; від природного старіння конструкційних електроізоляційних матеріалів; від погіршення електричних параметрів елементів антен внаслідок зволоження ізоляції їх активних елементів.

Кавітаційна міцність залежить від параметрів робочого середовища локаційних засобів (величини заглиблення антени, температури, вмісту газу) та параметрів антени (частоти випромінювання звуку, тривалості випромінюваних імпульсів, їх шпаруватості, нерівномірності коливальної швидкості та акустичного тиску на поверхні випромінювання антени та перетворювачів).

Визначені аналітичні співвідношення для розрахунків рівнів механічної та електричної міцностей в залежності від акустичної енергії, що випромінюється локаційним засобом, що дозволяє здійснювати пошук технічних шляхів підвищення рівня випромінюваної акустичної енергії, залишаючи допустимими рівні електричної, механічної та кавітаційної міцностей.

Ключові слова — електрична; механічна; кавітаційна міцності; потужність акустичного випромінювання; аналітичні залежності.