Journal of Siberian Federal University. Mathematics & Physics 2022, 15(1), 101–107

DOI: 10.17516/1997-1397-2022-15-1-101-107
УДК 534(075)

On Seawater Conductivity Control by Acoustic Radiation

Georgy Ya. Shaidurov*
Danil S. Kudinov†
Aleksey N. Fomin‡
Siberian Federal University
Krasnoyarsk, Russian Federation

Received 20.05.2021, received in revised form 10.07.2021, accepted 20.09.2021

Abstract. The article presents the results of studying the acoustic radiation affecting the conductivity of the seawater (a solution of salt (NaCl) in water). At a salinity of 35 g/L (‰), pressure of 500–2500 Pa (Pascal), and power flux density for acoustic vibrations within 0.5–2.5 W/m, the conversion coefficient for the electromagnetic field frequency under acoustic radiation varied from 10^{-4} to $2\cdot 10^{-2}$. At a salinity of 12 g/l (‰), the authors observed a slump for this coefficient. Compared to the effect of hydrostatic pressure on the conductivity of seawater, ultrasound is three orders of magnitude more intense. The materials of the article can be applied to the problems of maritime communications and geophysics.

Keywords: electrolyte, seawater, acoustic radiation, control, conductivity, transformation, frequency.

Citation: G.Ya. Shaidurov, D.S. Kudinov, A.N. Fomin, On Seawater Conductivity Control by Acoustic Radiation, J. Sib. Fed. Univ. Math. Phys., 2022, 15(1), 101–107.
DOI: 10.17516/1997-1397-2022-15-1-101-107.

In 1993, the famous Danish electrochemist Peter Debye conducted an experiment and discovered oscillations of the electric potential in an electrolyte solution under ultrasound and made an equation of this phenomenon, later called the Debye effect [1]. When introduced to a salt solution under acoustic pressure, the ions of different masses displaced and caused oscillations of electrical potential. Naturally, the solution ionization affected the local temperature, viscosity, conductivity of the water, and other parameters. Since then, researchers published plenty of articles on studying this phenomenon and its applications. A detailed edition of Ultrasound and its Use in Science and Engineering (1957) by L. Bergman was translated into Russian and published by Moscow Foreign Language Publishing House [1]. The book describes the results of theoretical and experimental studies carried out by various researchers, i.e. [2–4]. Scholars published several curious studies on the ultrasound effect on physiological solutions, biological tissues, and blood in vitro in small cuvettes for biomedical application [5–8]. Study [5] gives a detailed consideration of the phenomena such as ultrasound causing electrical signals in biochemical solutions. It provides the equation for the changes in relative conductivity depending on the ultrasound pressure. In this case, 47‰ of the changes in conductivity are accounted for by the volumetric compressibility, 18‰ by the mobility of ions, and 35‰ by the temperature changes. However, the composition of the electrolytes under consideration is way more complex than seawater; therefore, the results of these studies require clarification within the problem described in this article. The mining industry makes good use of ultrasound in solutions enrichment

*gshy35@yandex.ru
†kudinovdanil@yandex.ru
‡fomin.1951@bk.ru

technology. Ivanov [9], Frenkel [10], Biot [11], and Svetov [12] studied various aspects of seismic radiation effect on the electrical parameters of rocks and their discontinuity surfaces. The practice of geophysics noted abrupt changes in the electrical resistance of rocks under seismic shocks caused by changes in the electrical conductivity of saline water under acoustic pressure [13]. The Debye effect applied to maritime communications, location, and navigation was studied at Far Eastern Federal University (the research on the interaction of forward-scattering acoustic and electromagnetic waves when transmitting information along the large routes in the ocean or hydroacoustic pool [14]) and by the authors [15–17] of this article. The main challenge of these studies was the development of a highly sensitive experimental procedure to assess the quantitative dependences of the conductivity of seawater on acoustic pressure with a relative sensitivity of measurements 10^{-6}–10^{-7}. This article describes the results of experiments in a laboratory pool with tap water with a high concentration of $NaCl$ which is the most abundant component of seawater. The $NaCl$ concentration in seawater is almost 10 times higher than the concentration of magnesium or other salts. In this case, we can assume that 18 the investigated electrical conductivity of the solution corresponds to seawater.

1. Theoretical assessment

According to a theoretical assessment made by the authors [4], the dependence of the electrolyte conductivity on its temperature changing under acoustic pressure is:

$$M_\sigma = \frac{\Delta\sigma}{\sigma_0} = \left(\frac{B}{T_0^2} - \frac{1}{T_0}\right) \cdot \frac{\sqrt{2\rho V_a I} \cdot 10^5}{2\gamma}. \tag{1}$$

Hhere σ_0 is the electrical conductivity of water unaffected by ultrasounda;

ρ is the water density;

V_a is the speed of sound;

$\gamma = 0.37 \cdot 10^6$ is a constant depending on the medium structure for NaCl solution at $T = 20°$;

T_0 is the water temperature;

$B = 48.1 \cdot T_0$;

I is the power flux density for acoustic vibrations.

If I =1 W/m^2, T = 5°C, ρ=103 kg/m^3, V_a=1500 m/s, σ_0=4 S/m; salt concentration is 5.9‰, then the relative change in the conductivity of water under ultrasound is:

$$M_\sigma = \frac{\Delta\sigma}{\sigma_0} = 0.7 \cdot 10^{-3}. \tag{2}$$

From (2) and (3), we see that m_σ does not depend on the ultrasound frequency. However, when we affect the water conductivity by acoustics according to the harmonic motion, the coefficient m_σ decreases by half. If we apply an external electromagnetic wave with a frequency ω_e close to ω_a to the water, then the components of the combination frequencies $\omega_e \pm \omega_a$ appear in the voltage in the water as a result of parametric multiplication of the electromagnetic and acoustic fields. The current density can be written as:

$$j_x = E_x \cdot \sigma = E_x \cdot \sigma_0 \cdot \{sin(\omega_e t + \varphi_e) + 0.5 M_\sigma \cdot sin\left[(\omega_e \pm \omega_a)t + \varphi_e\right]\}. \tag{3}$$

This is the parametric transformation of the electromagnetic field from high frequency ω_e to low frequency $\Omega = \omega_e - \omega_a$ in the skin layer. When the ultrasound from a submersible irradiates the sea surface, signals from ground radio stations can be received using a submersible antenna at a frequency of Ω with no need for the craft to surface.

2. Experimental results

In October 2018, the authors conducted an experiment in a saltwater pool of 500×500×1300 mm, 320 liters (see Fig. 1). They generated the electric field $f_e = 16470$ Hz in the water using titanium plates immersed in the solution from the opposing edges of the pool; the reception was carried out to an electric dipole 20 cm long through non-polarizable electrodes with the difference frequency f_e—f_a=1.47 kHz and closed in an RLC circuit.

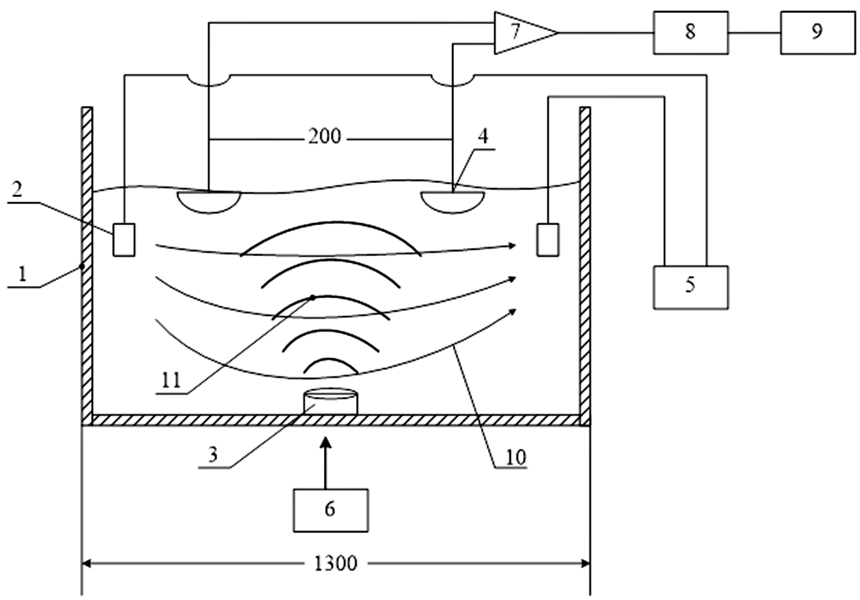

Fig. 1. Experimental facility scheme: 1 — pool; 2 — titanium electrodes; 3 — acoustic vibrator; 4 — receiving non-polarizable electrodes; 5 — generator of electrical oscillations; 6 — ultrasound generator; 7 — amplifier; 8 — ADC; 9 — micro PC; 10 — electric flux; 11 — ultrasonic beam

A vibrator up to 15 W affected the water surface using ultrasound with frequency $f_a = 15$ kHz. Near the receiving dipole, the range of acoustic radiation power flux density was 0 – 2.5 W/m^2. The concentration of sodium chloride in the water varied from 0 to 35 g/L (35 ‰). The personal computer recorded the difference signal of $F = f_e — f_a$ frequency through 24-bit ADC from the secondary winding of the oscillatory circuit. The parametric frequency conversion (PFC) parameter was estimated by the coefficient:

$$M = \frac{\Delta E_F}{E_f}, \tag{4}$$

Hhere ΔE_F is EMF (electromotive force) of the difference frequency $F = f_e — f_a$ on the primary winding of the oscillatory circuit, and E_f is EMF of the fundamental frequency.

The current passed through the pool was kept constant in the amplitude while the salt concentration changed. The authors controlled the amplitude of supply current for the vibrator by changing the power flux density for acoustic vibrations. Fig. 2 illustrates the dependence of m coefficient from S‰ salt concentration, I_a power flux density, and its pressure P, controlled by a geophone with a sensitivity of 40 μV/Pa.

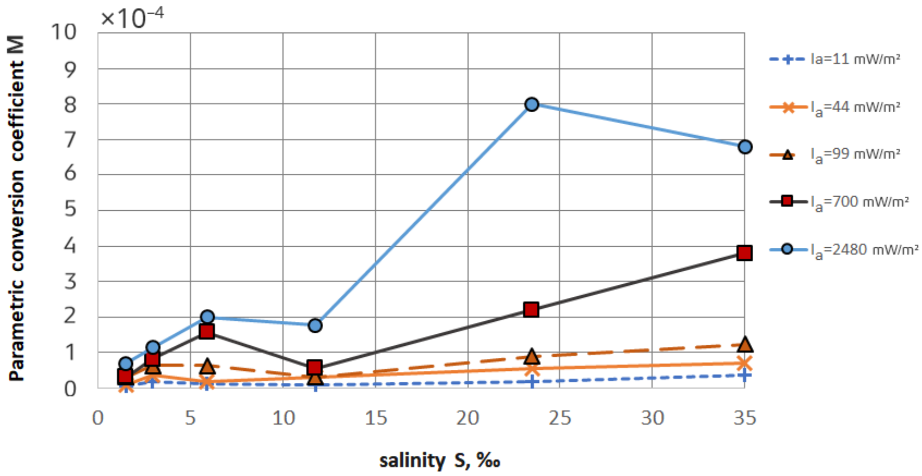

Fig. 2. Dependence of the parametric conversion coefficient on the salinity of the solution and the power flux density of acoustic radiation

Fig. 3 shows that within I_a=0.5 — 2.5 W/m^2, m coefficient grows both with the increasing of Ia and salt concentration S, g/l. When the salt concentration is about 12‰, we observe a slump for m coefficient. The authors can explain this phenomenon only by a change in the ionic bonds in the solution at this concentration, as no publication known to the authors describes this effect.

The authors obtained similar results in a larger laboratory pool, 500×500×1300 mm with a water mass of 6000 kg. The results didn't change when the authors used an induction loop and a linear horizontal antenna for the non-contact excitation of the electromagnetic field. As we can see, the theoretical assessment of the expected coefficient of parametric frequency conversion m_σ (3) almost the same for the similar initial parameters with the experimental data illustrated in Fig. 1a.

According to [18], the relative change in the conductivity of seawater under hydrostatic pressure is $M = \Delta\sigma/\sigma = 10^{-9}$/Pa, while the experimental results of the ultrasound effect resulted in M=10^{-6}/Pa. Thus, the alternating acoustic radiation affects the electrical conductivity of seawater by 3 orders of magnitude more intense than the hydrostatic pressure. The authors can explain this phenomenon by a significant change in the mobility of salt ions dissolved in water and the appearance of an additional electric moment in the electrolyte due to the difference in the masses of $NaCl$ salt ions, which generally confirms Debye's theory and can be applied to various problems of maritime communications and geophysics.

In particular, the [14] describes the patented *Method of Elastic Wave Transmission in Seawater* that proposed to use an electromagnetic field to superimpose on acoustic radiation at the same frequency, which allows increasing the efficiency of the antenna. The experiments carried out by the authors indicate the possibility of realizing this parametric effect.

Conclusion

Testing the parametric effect in a pool with salt water resulted in variable-frequency ultrasound influencing the electrical conductivity of saltwater with a corresponding seawater salt

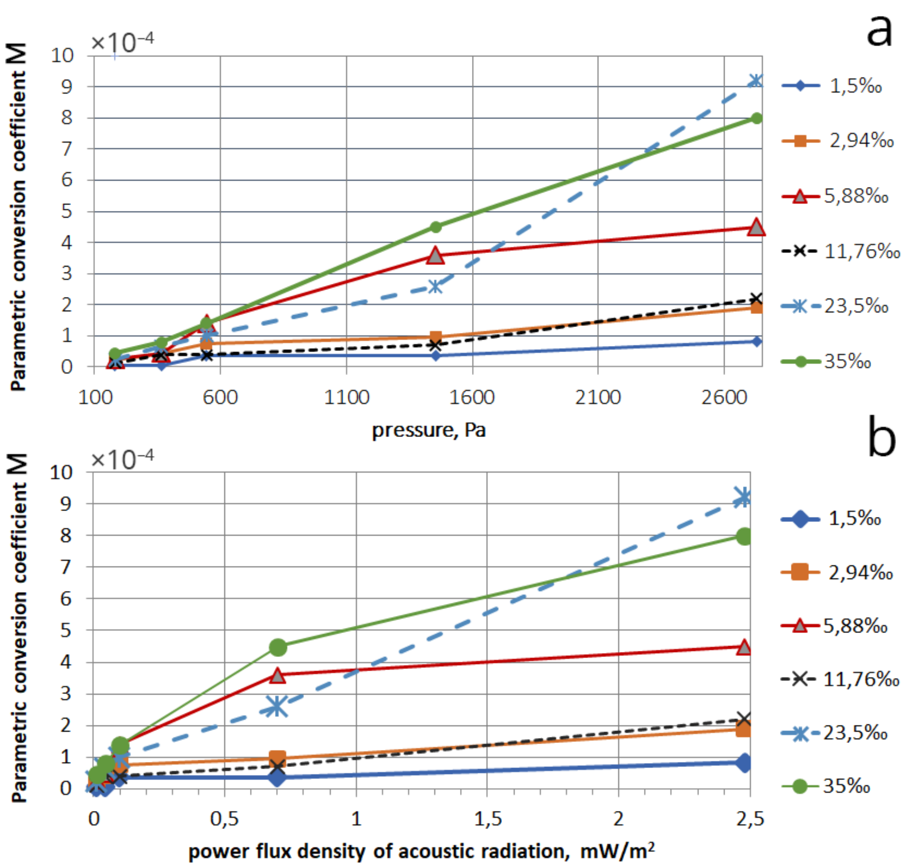

Fig. 3. Dependence of the parametric conversion coefficient on the salinity of the solution and the power flux density of acoustic radiation

concentration by three orders of magnitude stronger than the hydrostatic pressure. This is associated with the sharp increase in the mobility of the ions in the solution and the appearance of an additional electric moment in the direction of the ultrasound action.

In general, this confirms the theory of Debye et al. Meanwhile, the new data obtained with modern equipment by the authors significantly complement the quantitative value of the parametric effect.

This research is supported by a grant from the Russian Foundation for Basic Research (project no. 20-07-00267).

References

[1] L.Bergman, Ultrasound and its Use in Science and Engineering. Issue 2, Foreign Literature Publishing house, Moscow, 1957.

[2] S.Oka, Fortpflanzung der ultrakurzen schallwellen durch einen elektrolyten, *Proceedings of the Physico-Mathematical Society of Japan*, **3**(1933), 413–419.

[3] E.Yeager, F.Hovorka, Ultrasonic Waves and Electrochemical Applications of Ultrasonic Waves, *Journ. Acoust. Soc. Am.*, **25**(1953), 443.

[4] G.Ya.Shaidurov, D.S.Kudinov, G.N.Romanova, Effects of Parametric Interaction of Electromagnetic and Acoustic Waves in Seawater, *Memoirs of the Faculty of Physics, Moscow University*, **14**(2014), no. 6 (in Russian).

[5] J.Jossinet, B.Lavandier, D.Cathignol, The phemenology in acousto-electric interaction signals in aqueous solutions of electrolytes, *Ultrasonics*, **36**(1998), 607–613.

[6] Q.Li, R.Olafsson, P.Ingram, Z.Wang, R.Witte, Measuring the acoustoelectric interaction constant using ultrasound current source density imaging, *Phys. Med. Biol.*, **57**(2012), 5929–5941. DOI: 10.1088/0031-9155/57/19/5929

[7] B.Lavandier, J.Jossinet, D.Cathignol, Experimental measurement of the acousto-electric interaction signal in saline solution, *Ultrasonics*, **38**(2000), 929–936.

[8] F.Cataldo, Effects of ultrasound on the electrolytic conductivity of simple halide salts, *Electroanalytical Chemisty*, **431**(1997), 61–65.

[9] A.G.Ivanov, Electrification of Earth Layers upon Elastic Waves Passing through Them, *Report of USSR Academy of Sciences*, **24**(1939), no. 1.

[10] Ya.I.Frenkel, To the Theory of Seismic and Seismoelectric Phenomena in Wet Soil, *Isv. USSR Academy of Sciences. Geography and Geophysics series*, **8**(1994), no. 4, 133–150 (in Russian).

[11] M.A.Biot, Theory of Propagation of Elastic Waves in a Fluid-Saturated Porous Solid, *J. Acoust. Soc. Am.*, **28**(1956).

[12] B.S.Svetov, Electromagnetic Field of Mechanoelectrical Origin in Porous Water-Saturated Rocks. Problem Statement, *Fizika zemli*, (1999), no. 10, 67–63 (in Russian).

[13] P.A.Potapov, S.A.Lizun, et al., Fundamentals of Seismoelectric Exploration, Moscow: Nedra, 1995 (in Russian).

[14] M.I.Zvonarev, V.I.Korochentsev, M.V.Mironenko, S.V.Popov, Method of Elastic Wave Transmission in Seawater, RF patent 2167454(20.05.2001) (in Russian).

[15] G.Ya.Shaydurov, V.N.Lukiyanchikov, G.N.Romanova, On Parametric Demodulation of an Electromagnetic Wave by Ultrasound at the Water-Air Interface, *Radiotekhnika i Elektronika, Moscow,* **30**(1985), no. 11, 21–36 (in Russian).

[16] G.N.Romanova, G.Ya.Shaydurov, Parametric Demodulation of Electromagnetic Waves by Ultrasound at an Water–Air Interface, *Physics Soviet journal of communications technology & electronic*, **36**(1991), 108–110.

[17] G.Ya.Shaydurov, G.N.Romanova, D.S.Kudinov, Parametric Method of Underwater Radio Navigation in Arctic Conditions, *Journal of Communications Technology and Electronics*, **65**(2020), no. 8, 888–893. DOI: 10.1134/S1064226920070116

[18] N.I.Popov, K.N.Fedorov, V.M.Orlov, Seawater. Reference Guide, Nauka Publishing house, Moscow, 1979 (in Russian).

Об управлении проводимостью морской воды акустическим излучением

Георгий Я. Шайдуров
Данил С. Кудинов
Алексей Н. Фомин
Сибирский федеральный университет
Красноярск, Российская Федерация

Аннотация. В статье изложены результаты экспериментов по исследованию эффекта управления проводимостью морской воды (раствором поваренной соли в пресной воде) акустическим излучением. При солености 35 г/л (‰), давлении от 500–2500 Па (Паскаль) и плотности потока мощности акустического излучения в пределах 0.5–2.5 Вт/м коэффициент преобразования частоты электромагнитного поля акустическим излучением изменялся от 10^{-4} до $2 \cdot 10^{-2}$. При солености 12 г/л (‰) наблюдался резкий спад этого коэффициента. По сравнению с влиянием гидростатического давления на проводимость морской воды ультразвук действует на три порядка сильнее. Материалы статьи могут быть использованы в различных прикладных задачах морской связи и геофизики.

Ключевые слова: электролит, морская вода, акустическое излучение, управление, проводимость, преобразование, частота.