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Experimental investigation on the effective radiating area of ultrasonic transducers with the aim of increasing the reproduction accuracy of the unit of ultrasonic pressure in water

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Abstract

This paper presents the results of an experimental investigation on the effective radiating areas (A_{ER}) of auxiliary ultrasonic transducers forming part of the measurement standard for the unit of ultrasonic pressure in water NDETU AUV-02-2018. When carrying out measurements, the pressure field of MANA Instruments ultrasonic transducers E1025-SU; E2312-SU; E3512-SM has been subjected to raster scanning at operating frequencies using a raster scanning system. A positioning device for ultrasonic transducers was developed at DP NDI "Systema" in the process of creating the measurement standard NDETU AUV-02-2018, and forms its integral part. The A_{ER} calculation protocol has been developed based on IEC 61689. The type A uncertainty has been evaluated from ten repetitions of the full measurement procedure to determine the A_{ER}, and the type B uncertainty has been estimated from the A_{ER}-specific mathematical model based on IEC 61689 and DSTU-N RMG 43 "Metrology. Application of the Guide to the Expression of Uncertainty in Measurement".

Keywords: effective radiating area; ultrasonic beam; ultrasonic pressure; ultrasonic transducer; uncertainty.

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Introduction

The national (state primary) measurement standard for the unit of ultrasonic pressure in water (NDETU AUV-02-2018) reproduces the ultrasonic pressure unit – pascal (Pa) – by the two-transducer reciprocity method. An auxiliary ultrasonic transducer (UT) which is used in reproducing the ultrasonic pressure shall have a circular plane active surface and create an acoustic field that, by its properties, is very similar to the field of a circularly plane piston source [1]. The UT shall be passive, reversible, and reciprocal [2]. The reciprocal UT sensitivity in receiving the acoustic signal, and its sensitivity in radiating are related to one other by the reciprocity parameter (J_P). For the plane wave, the reciprocity parameter is a function of the effective radiating area, and is given by [3]

$$J_P = \frac{2 \cdot A_{ER}}{\rho \cdot c}, \tag{1}$$

where A_{ER} is the UT effective area, ρ is the water density, c is the speed of sound in water.

The ultrasonic pressure generated by the auxiliary UT can be determined using a mathematical model that relates the measured electrical parameters and acoustical parameters of the UT, and those of the propagation medium (water):

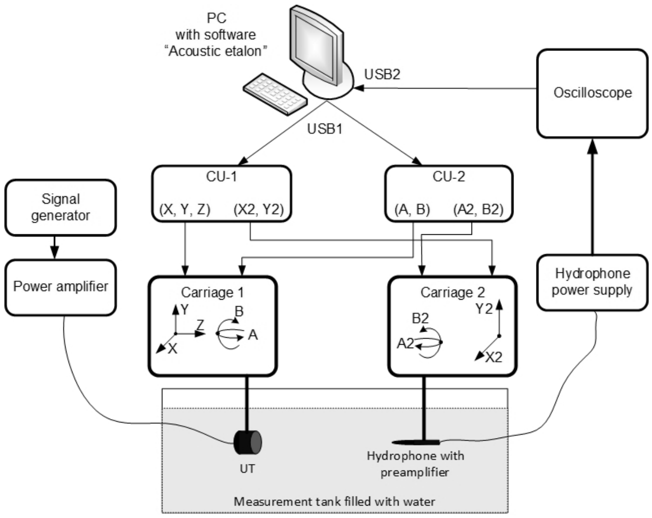
$$P = \sqrt{\frac{U \cdot I}{r \cdot G \cdot e^{-\alpha d} \cdot J_P}} = \sqrt{\frac{U \cdot I \cdot \rho \cdot c}{r \cdot G \cdot e^{-\alpha d} \cdot 2 \cdot A_{ER}}}, \tag{2}$$

where I is the current through the UT with an ultrasonic signal being radiated; U is the UT voltage being a response to the UT-radiated acoustic signal reflected off the reflector; r is the reflector reflection coefficient; G is the diffraction loss coefficient; α is the attenuation coefficient of ultrasound in water; d is the measurement distance; A_{ER} is the effective radiating area; J_p is the reciprocity coefficient.

As it is seen from the mathematical model for the ultrasonic pressure, the UT effective radiating area value (A_{ER}) influences the accuracy of the pressure reproduced, and the A_{ER} uncertainty is a component of the combined uncertainty for the ultrasonic pressure unit reproduction by NDETU AUV-02-2018.

Objective of the paper

To determine the auxiliary UT effective radiating area value that influences the accuracy in reproducing the unit of ultrasonic pressure in water, as well as its uncertainty, which is a component of the combined uncertainty for the ultrasonic pressure unit reproduction by NDETU AUV-02-2018.



Keys:

CU-1 – control unit for linear displacement along the axes X, Y, Z, X2, Y2

CU-2 – control unit for angular displacement around the axes A, B, A2, B2

PC – personal computer

UT – ultrasonic transducer

Fig. 1. Functional schematic of the raster scanning system

Raster scanning system for ultrasonic field

In order to determine the UT effective radiating area, a raster scanning system for the UT ultrasonic field has been created, which comprises:

– a hydrophone positioning fixture (HPF) being a component of NDETU AUV-02-2018;

– measuring equipment (signal generator, power amplifier, oscilloscope, hydrophone);

– a measurement tank filled with water, 985×385×490 mm (150 liter capacity) whose dimensions are sufficient to perform acoustic measurements of the UT characteristics in the frequency range 1 to 10 MHz;

– a personal computer with the software application "*Acoustic etalon*". Fig. 1 illustrates the functional schematic of the raster scanning system.

The HPF is intended for the spatial positioning (placement and mutual orientation) of the hydrophone and the UT in the measurement tank, consists of two angle bar carriages on which the UST and the hydrophone are mounted. The HPF ensures the linear displacement for the UT along the axes X (0–90 mm), Y (0–430 mm), Z (0–640 mm), for the hydrophone along the axes X2 (0–90 mm), Y2 (0–430 mm), and the horizontal and vertical rotation for the UT around the axes A (–20° to +20°), B (–20° to +20°), for the hydrophone around the axes A2 (–20° to +20°), B2 (–20° to +20°). The HPF resolution is 2 μm for the linear displacement, and 0.01° for the angular displacement.

The developed software application "*Acoustic etalon*" enables the user to enter a scan step, a total number of scan steps to be performed by the hydrophone (for the axes X2, Y2), and a time delay to avoid water agitation due to hydrophone displacements, and to correctly measure the voltage at each scan point. The software application automatically scans the UT ultrasonic field by displacing the needle hydrophone with respect to the UT that remains still during the scanning procedure, and records the values of the hydrophone output voltages at each scan point, displays the results on the user screen, and saves them into a particular file after completion of the scanning procedure. A general view of the software application "*Acoustic etalon*" is given in Fig. 2.

Determination of the effective radiating area of the UT

The effective radiating area of the auxiliary UT is the auxiliary UT surface area which contains 100%

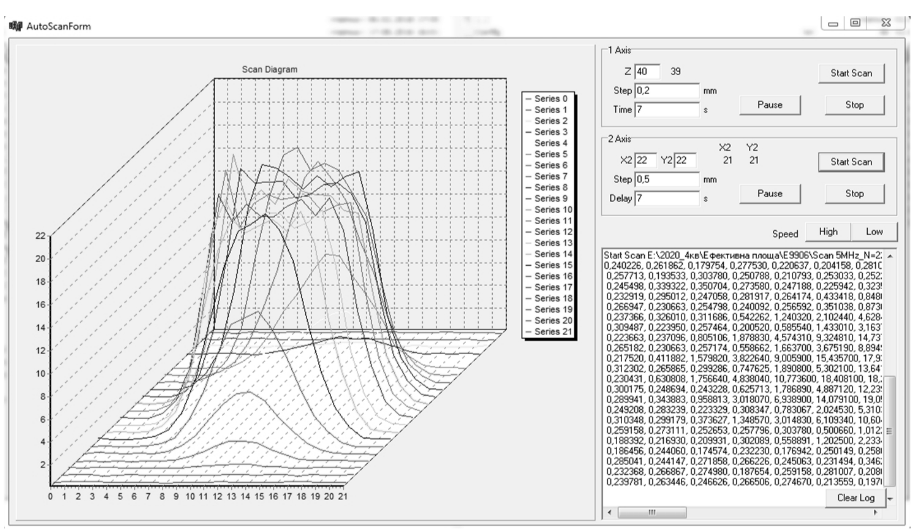


Fig. 2. Software application "Acoustic etalon" for raster scanning

of the total mean square acoustic pressure generated by it. The effective radiating area is determined by the formula [3]

$$A_{ER} = A_{BCS}(0.3) \cdot F_{ac}, \qquad (3)$$

where A_{BCS} (0.3) is the minimum area in the plane at a distance of 0.3 cm from the front of the UT, perpendicular to the beam alignment axis, for which the sum of the mean square acoustic pressure is 75% of the total mean square acoustic pressure; F_{ac} = 1.333 is the dimensionless factor.

The effective radiating area of the UT has been investigated according to [3] and determined by the raster scan method using a needle hydrophone whose effective radius shall not be greater than 0.4 times the wavelength at a frequency of interest. Scans have been performed in a specified plane perpendicular to the beam alignment axis at a distance of 0.3 cm from the front of the UT. The geometrical centre of the UT has been chosen as an initial point of raster scanning with the assumption that the ultrasonic beam alignment axis coincides with its geometrical centre. The scan step and the number of scan points on the axes X2, Y2 have been chosen such that the hydrophone linear displacement exceeds the UT geometrical diameter and covers the entire UT geometrical area.

The generator AFG 3021C and the power amplifier A150 have been used to apply to the UT a sinusoidal tone burst signal of operating frequency (a 20–30-cycle duration), and the oscilloscope TDS 2024C has been used to measure the hydrophone output voltage in each scan point. A measurement schematic is shown in Fig. 1.

In order to determine the beam cross-sectional area, A_{BCS}(0.3), the obtained voltages have been sorted into a set in descending order to find the value of the number of voltages, N, that satisfies the following relationship:

$$\sum_{i=1}^{n} \frac{U_i^2}{M_L^2} \le 0.75 \sum_{i=1}^{N} \frac{U_i^2}{M_L^2} < \sum_{i=1}^{n+1} \frac{U_i^2}{M_L^2}, \qquad (4)$$

where M_L is the hydrophone sensitivity; U_i is the hydrophone output voltage in the i-th scan point, n is the number of scan points.

Then, the value of the beam cross-sectional area, A_{BCS}(0.3), has been determined as

$$A_{BCS}(0.3) = s^2 \cdot N, \qquad (5)$$

where s is the raster scan step; N is the number of voltage values obtained after sorting, which satisfy the requirement (4).

For reliable determination of A_{BCS}(0.3), the number of points, n, included in the determination of A_{BCS}(0.3), should be at least 100.

Thus, the UT effective radiating area, A_{ER}, according to (3) and (5) has been determined as

$$A_{ER} = F_{ac} \cdot s^2 \cdot N. \qquad (6)$$

Analysis of sources and calculation of the uncertainty of the effective radiating area measurement

The type B standard uncertainty of the scan step s, $u_{s(B)}$, depends on the chosen number of scan steps, i.e. on the displacement length along the axes X2, Y2 and the resolution of the raster scanning system (2 μm). The system resolution refers to the type B uncertainty, and is estimated to be half the system resolution value for the rectangular probability distribution, i.e. $u_{s\_resol(B)}$ = 2/2√3.

According to the manufacturer of the ball screw pair used for linear displacement in the scanning system, the irreducible (inherent) additive error through a displacement of 1 cm is equal to 1.7 μm. Under the rectangular probability distribution assumption, $u_{s\_add(B)}$ = 3.4*1.7/√3 (for a linear displacement of 3.4 cm). Therefore, the type B standard uncertainty of the scan step, $u_{s(B)}$, has been determined as

$$u_{s(B)} = \sqrt{u_{s\_resol(B)}^2 + u_{s\_add(B)}^2}.$$

The type B standard uncertainty of the parameter N, $u_{n\_(B)}$, depends on three sources: measurement of the r.m.s. value of the AC output voltage of the hydrophone by using an oscilloscope, $u_{n\_osc(B)}$, of the linearity of the measurement system "hydrophone + preamplifier+ + power supply (matching) + oscilloscope", $u_{n\_lin(B)}$, and of the hydrophone sensitivity, $u_{n\_M(B)}$. However, the hydrophone sensitivity and its uncertainty may be neglected according to [3], since the absolute values of the acoustic pressure are not required and the analysis of measured data in this work is based on relative hydrophone measurements of the voltage (4), therefore $u_{n\_M(B)}$ = 0.

According to the calibration certificate, the expanded uncertainty of the oscilloscope is equal to 3% for the normal probability distribution, therefore $u_{n\_osc(B))}$ = 3/√2.

The linearity of the measurement system has been checked using a separate UT operating in tone-burst mode, and measuring with the oscilloscope the voltage received by the hydrophone as a function of voltage excitation applied to the UT. The oscilloscope has been set up for a measuring range of 0 mV to 100 mV. The system linearity has been determined at the points of 10 mV, 25 mV, 50 mV, 75 mV, 100 mV at the maximum deviation of the measured voltage value from the best-fit regression line. The system linearity does not exceed 0.8% for the normal probability distribution in the measuring range 10 mV to 100 mV, therefore $u_{n\_lin(B)}$ = 0.8/√2. The type B standard uncertainty of the parameter N, $u_{n(B)}$, has been determined as

$$u_{n(B)} = \sqrt{u^2_{n\_osc(B)} + u^2_{n\_lin(B)} + u^2_{n\_M(B)}}.$$

According to Annex E [3], the standard uncertainty for the value of F_{ac} = 1.333 is taken equal to zero.

The type A standard uncertainty of the effective radiating area of the UT, ($\boldsymbol{u}_{A_{ER}(A)}$), has been determined from a series of 10 independent observations in accordance with [4]. To allow for all possible errors associated with the UT and hydrophone adjustment, for each individual measurement, the UT and hydrophone have been remounted and readjusted. Adjustment depends on the positioning accuracy and fastening technique of the UT and hydrophone, and on the operator skills.

According to [4], the combined standard uncertainty, u_c, for any $y = f(x_i)$ function associated with the measurement result, is determined by the formula

$$u_c^2 = \sum_{i=1}^{n} \left(\frac{\partial y}{\partial x_i} \right)^2 \cdot u_i^2,$$

where u_i is the type A or B evaluation of standard uncertainty associated with the corresponding variable x_i used to determine the value of the function y; $\partial y / \partial x$ is the sensitivity coefficient with respect to the variable x_i.

For the effective radiating area, the sensitivity coefficients associated with the parameters F_{ac}, s, N are obtained by partial differentiation of the formula (6) with respect to a corresponding parameter, and they are as follows:

$$c_{Fac} = \frac{\partial A_{ER}}{\partial F_{ac}} = 1;\; c_s = \frac{\partial A_{ER}}{\partial s} = 2;\; c_n = \frac{\partial A_{ER}}{\partial n} = 1.$$

The combined standard uncertainty of the UT effective radiating area has been determined as

$$u_{c(A_{ER})} = \sqrt{\begin{aligned}&\left(u_{s(B)} \cdot c_s\right)^2 + \left(u_{n(B)} \cdot c_n\right)^2 + \\ &+\left(u_{Fac(B)} \cdot c_{Fac}\right)^2 + u^2_{A_{ER}(A)}\end{aligned}}.$$

A calculation example of the uncertainty budget for the A_{ER} of the E1025-SU at frequency 1 MHz (1 mm scan step, 34×34 mm scan area) is given in Table 1.

Results of the investigation

The raster scan of the ultrasonic pressure field has been carried out for three types of ultrasonic transducers: *Mana Instruments* E1025-SU; E2312-SU; E3512-SM that have been used during the reproduction of the ultrasonic pressure unit by the measurement standard in the frequency range 1 MHz to 4 MHz. Technical characteristics of the UTs and their operating frequencies are given in Table 2.

An example of the arrays of voltage values obtained during the scan for different types of UTs that have been used in determining the parameter N, and calculating the UT effective radiating areas, A_{ER}, is given in Fig. 3.

Table 1

Uncertainty budget for the A_{ER} of the E1025-SU at frequency 1 MHz

Value	Estimate	Standard uncertainty, u_i	Probability distribution	Sensitivity coefficient, c_{xi}	Uncertainty contribution, %	$u_{cA_{ER}}$, %	k (P = 0.95)	U, %
Scan step s, mm/$\boldsymbol{u}_{s(B)}$	1.0	0.0034	normal	2	0.68	1.74	2.0	3.48
$\boldsymbol{u}_{s\_resol(B)}$, mm		0.0006	rectangular					
$\boldsymbol{u}_{s\_add(B)}$, mm		0.0010	rectangular					
Parameter $\boldsymbol{n}$/$\boldsymbol{u}_{n(B)}$	276	1.55	normal	1	1.55			
$\boldsymbol{u}_{n\_osc(B)}$, %		1.5	normal					
$\boldsymbol{u}_{n\_lin(B)}$, %		0.4	normal					
Parameter $\boldsymbol{F}_{ac}$/$\mathbf{u}_{Fac(B)}$	1.333	0	normal	1	0.0			
$\mathbf{u}_{A_{ER}(A)}$, %		0.39	normal	1	0.39			

Table 2

Technical characteristics of the UTs and their operating frequencies

UT type	Diameter, mm	Geometrical area, mm^2	Operating frequency, MHz
E1025-SU	25	490.87	1
E2312-SU	12.7	126.68	2, 3
E3512-SM	12.7	126.68	2, 3, 4

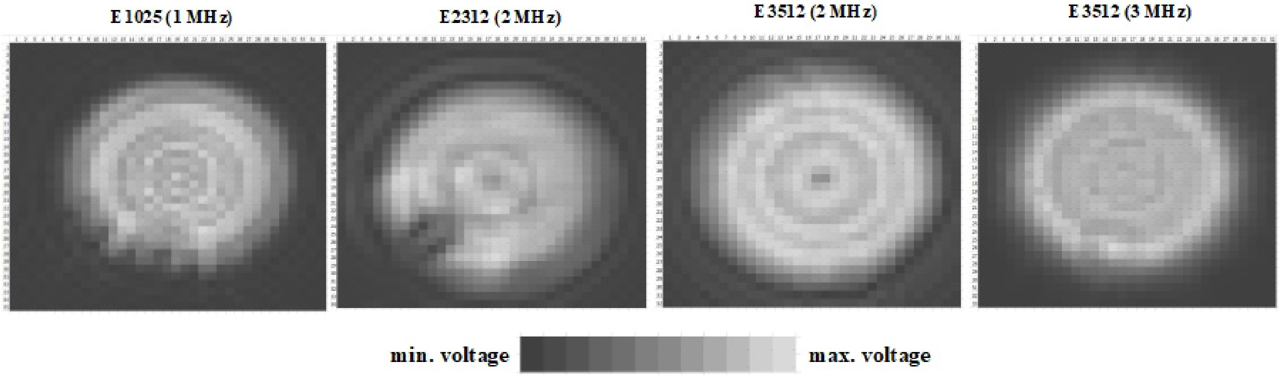


Fig. 3. Results of the UT ultrasonic field scanning

Table 3

The results of determining the A_{ER} of the auxiliary UTs obtained by automated raster scanning

UT type	Frequency, MHz	Geometrical area, mm^2	Effective radiating area, mm^2	RMSD, %	Difference in size of A_{ER} compared to geometrical area, %
E1025-SU	1.0	490.80	368.32	0.45	-25.0
E2312-SU	2.0	126.68	89.88	0.63	-29.05
	3.0		96.88	0.39	-23.52
E3512-SU	2.0	126.68	104.14	1.55	-17.79
	3.0		101.98	0.62	-19.50
	4.0		105.57	0.39	-16.66

Table 4

The results of calculation the auxiliary UT effective areas and their uncertainty

UT type	Frequency	Scan step	Scan size (X2, Y2)	Parameter N	Effective radiating area	u_C	k	Expanded uncertainty, U
	MHz	mm	mm	—	mm^2	%	P = 0.95	%
E1025-SU	1	1.0	34	276	368.32	1.74	2	3.48
E2312-SU	2	0.5	32	268	89.88	2.05	2	4.1
	3	0.5	32	290	96.88	2.15	2	4.3
E3512-SU	2	0.5	32	306	104.14	2.58	2	5.16
	3	0.5	32	316	101.98	2.26	2	4.52
	4	0.5	32	318	105.57	2.37	2	4.74

The results of determining the A_{ER} of the auxiliary UTs obtained by automated raster scanning, and difference in size of the A_{ER} compared to the geometrical area are given in Table 3.

The results of calculating the auxiliary UT effective radiating areas are given in Table 4.

Conclusion

Based on the experimental investigation results, the values of the UT effective radiating areas have been obtained, which form part of the national measurement standard NDETU-AUV-02-2018, at operating frequencies, and their uncertainty has been evaluated. The results obtained have made it possible to pass from applying the UT geometrical area in the mathematical reproduction model of the ultrasonic pressure in water to applying the UT effective radiating area, which in turn has made it possible to fulfill the requirements of [5], as well as to increase the accuracy of reproducing the unit of ultrasonic pressure in water by the NDETU-AUV-02-2018.

It should be mentioned that the raster scanning system and the software application, which have been developed, can be used in determining the treatment head parameters of medical ultrasonic physiotherapy equipment, such as radiation intensity, effective radiating area, and power, requirements to which are specified in IEC 61689. This equipment is widely used in Ukraine for treatment of soft tissues, musculoskeletal system in the frequency range 0.5 MHz to 3.0 MHz, but, for the time being, it falls outside the scope of state metrological supervision. Since the high intensity levels of the treatment ultrasonic heads can result in excessive heat, shock waves and cavitation which can damage human tissues, therefore the measurement and control of their parameters when performing the conformity assessment or operation procedures, as well as after repair are of current interest.

Дослідження ефективної площі ультразвукових перетворювачів для підвищення точності відтворення одиниці ультразвукового тиску у воді

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Анотація

Національний державний первинний еталон одиниці ультразвукового тиску у водному середовищі (НДЕТУ AUV-02-2018) відтворює одиницю ультразвукового тиску – паскаль (Па) методом взаємності з двома ультразвуковими перетворювачами (УП). Відповідно до математичної моделі визначення ультразвукового тиску, яка пов’язує вимірювані електричні параметри (струм УП під час випромінювання акустичного сигналу, напруга на УП під час прийому акустичного сигналу) і акустичні параметри УП та середовище поширення (вода), значення ефективної площі випромінювання ультразвукового перетворювача (A_{ER}) впливає на точність відтвореного тиску, а невизначеність A_{ER} є складовою загальної невизначеності відтворення ультразвукового тиску, який відтворює еталон. Для визначення ефективної площі випромінювання ультразвукового перетворювача створено систему растрового сканування з програмним забезпеченням для автоматичного сканування ультразвукового поля перетворювача та реєстрації результатів вимірювання.

У цій роботі надано результати дослідження ефективних площ випромінювання (A_{ER}) допоміжних ультразвукових перетворювачів еталона ультразвукового тиску у воді НДЕТУ AUV-02-2018. Під час вимірювання проводили растрове сканування поля тиску ультразвукових перетворювачів E1025-SU; E2312-SU; E3512-SM фірми MANA instruments на робочих частотах (від 1 до 4 МГц) за допомогою системи растрового сканування. Пристрій для позиціювання ультразвукових перетворювачів та гідрофонів розроблений в ДП НДІ “Система” під час створення еталона НДЕТУ AUV-02-2018 та входить до його складу. Протокол обчислення (A_{ER}) було розроблено на основі стандарту IEC 61689:2013 “Ультразвук – Фізіотерапевтичні системи – Характеристики вихідного поля та методи вимірювання в діапазоні частот від 0,5 МГц до 5 МГц”. Невизначеність за типом А було оцінено з десяти повторень повної процедури вимірювання для визначення A_{ER}, а невизначеність типу В було оцінено з математичної моделі для A_{ER} на основі IEC 61689:2013 та ДСТУ Н РМГ 43-2001 “Настанови щодо визначення непевності вимірювань”.

Ключові слова: ефективна площа випромінювання; ультразвуковий промінь; ультразвуковий тиск; невизначеність вимірювання.

Исследование эффективной площади ультразвуковых преобразователей для повышения точности воспроизведения единицы ультразвукового давления в воде

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Аннотация

В данной работе представлены результаты исследования эффективных площадей излучения (A_{ER}) вспомогательных ультразвуковых преобразователей эталона ультразвукового давления в воде НДЕТУ AUV-02-2018. При измерении проводили растровое сканирование поля давления ультразвуковых преобразователей E1025-SU; E2312-SU; E3512-SM фирмы MANA instruments на рабочих частотах посредством системы растрового сканирования. Устройство для позиционирования ультразвуковых преобразователей разработано в ГП НИИ "Система" при создании эталона НДЕТУ AUV-02-2018 и входит в его состав. Протокол вычисления (A_{ER}) был разработан на основе стандарта ДСТУ IEC 61689:2018. Неопределенность по типу А была оценена из десяти повторений полной процедуры измерения для определения A_{ER}, а неопределенность типа В была оценена по математической модели для A_{ER} на основе ДСТУ IEC 61689:2018 и ДСТУ Н РМГ 43-2001 "Руководства по определению неопределенности измерений".

Ключевые слова: эффективная площадь излучения; ультразвуковой луч; ультразвуковое давление; неопределенность измерений.

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