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Reciprocity Calibration of Hydrophones in High Intensity Focused Ultrasound Field

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Abstract: The primary problem of safety and efficiency for the high intensity therapeutic ultrasound (HITU) is the acoustic measure and dose control. The key technique is the pressure and intensity in the acoustic field especial in the focal region using the small calibrated hydrophone. The calibration accuracy of the used hydrophone is very important for HITU. Although the small hydrophone calibration has realized but there was no report of the hydrophone calibration in high pressure field. In this paper, our objective is to develop an absolute calibration method for the measurement of free field voltage sensitivity of hydrophone for high intensity focused ultrasound. First the acoustic pressure at the focal point by the self-reciprocity method of spherically curved auxiliary transducer is calibrated, then the free field voltage sensitivity of hydrophone at the geometric focal point of the calibrated pressure is obtained. The spatial average effect of acoustic pressure on hydrophone surface at the focal point is theoretically modified, and the expression and value table of correction coefficient of spatial average effect of hydrophone are given. The maximum acoustic pressure measured at the focal point was up to 5.58MPa (1.02kW/cm^2) and used to calibrate a hydrophone from 0.95 MHz to 1.10 MHz with maximum local distortion parameter 0.72. The results show the rationality and feasibility of the measurement principle and method.

keywords: High Intensity Focused Ultrasound (HIFU), Self-reciprocity Method, Hydrophone Calibration

1. Introduction

High intensity focused ultrasound (HIFU) has been widely used in clinical treatment. The acoustic filed performance is a decisive factor that governs the device's range of applicability, efficiency and quality control in manufacturing and application of HIFU therapeutic instrument. With the improvement of sound field theory and the progress of micro hydrophone technology, the measurement technology of spherical focused ultrasonic field has been mature, and the national and international standard have been established. [1, 2] In 2002, W Shou proposed the absolute calibration method of transmitting voltage (current) response and receiving voltage sensitivity of spherical focused transducer, and then it has been applied to acoustic power measurement and hydrophone calibration.[3-6] GB/T19890-2005 [7] is the first national standard for HIFU measurement in the world, it was cited by the IEC and NPL (British National Physical Laboratory) technical reports [8-9], which stipulates that hydrophone method is the standard method of HIFU acoustic field parameter measurement. Sensitivity is an important performance parameter of hydrophone, and it is the basis of hydrophone used for acoustic field measurement. Therefore, in order to ensure the accuracy of HIFU acoustic field measurement, it is necessary to calibrate the sensitivity of high-intensity hydrophone.

There are no standardized measurement methods applied for calibration of hydrophone under high acoustic pressure. In this paper, a feasible absolute calibration method for measuring the free field voltage sensitivity of hydrophones in high intensity focused ultrasound field was firstly proposed, using self-reciprocity method of spherically curved transducer to calibrate the transmitting response to current (voltage) and the pressure at the geometric focal point of an auxiliary transducer under high power excitation, then calibrating the free field voltage sensitivity of the hydrophone at the geometric focal point.

2. Calibrate the High Pressure of the Auxiliary Transducer of High Intensity Focused Ultrasound

HIFU concentrates ultrasonic waves into the body through certain means (acoustic lens, concave spherically self-focusing, electron focusing, etc.) to form a high-intensity focused region in ultrasonic sound field. The mechanical effect, thermal effect and cavitation effect of ultrasound can be used to achieve high temperature at the focal point instantly (0.5~2 s), so as to achieve the purpose of inactivating tumor tissue and avoid damage to surrounding normal cells. Currently, the acoustic power of high intensity focused ultrasound used clinically is usually within the range of hundreds of W/cm^2, therefore, we need high-volume powered hydrophone which have good linearity for high acoustic pressure field, temperature stability, a definite frequency response range, high temperature and impact resistances. At present, there is no perfect special needle hydrophone for high intensity focused ultrasound field measurement except expensive fiber optic sensor. The existing commercial PVDF hydrophone can't be used for high intensity acoustic field measurement for thermal damage. The dynamic range of piezoelectric ceramic hydrophone is infinite and its active element is easily damaged in high pressure. The hydrophone used in this experiment is a new specially designed PVDF high-intensity needle hydrophone of diameter 0.6 mm in applying for a patent. The PVDF hydrophone is of the tolerability of the short time high temperature and high pressure of HIFU but with low sensitivity [10, 11]. L Li conducted the plane scanning method in the focal plane of HIFU field to calibrate the HIFU hydrophone where the source acoustic power was measured by radiation force balance [12-15]. But it is very time-consuming and with more error. Although the hudrophone was used to measure the pressure at focal point for 7 HIFU tumor therapeutic equipments (the maximum output power up to 400W) in 2004-2005 and the National Standard of HIFU measurement was drafted in China in 2005, the real maximum pressure can't be still gotten simply so there was no feasible primary method of the hydrophone calibration in high pressure field. The key technique is to calibrate the high pressure of the auxiliary transducer of HIFU. Applying IEC TS 62903-2018 the high-pressure source has been calibrated as expressed below.

2.1. Measurement of Transmitting Response to Voltage of High Intensity Focused Transducer

The working frequency of high-intensity focused ultrasound is usually about 1MHz, therefore, the PA885 spherically curved focused transducer of PA company was selected in the experiment, with a resonant frequency of 1MHz, a nominal aperture of 60mm and a geometric focal length of 75mm. The degassed water of oxygen concentration 2.61ppm is used-to avoid cavitation during calibration。

Measure the effective half-aperture of transducer according to IEC62903. The measurement apparatuses are arranged as shown in Figure 1. The hydrophone measures scanning of hydrophone along the x axis and the y axis in the focal plane (x, y, F_{geo}) determined two pairs of -3 dB and -6 dB beam width respectively, and their average value are W_{pb3}=2.17mm, W_{pb6}=2.92mm, the effective radius of the transducer was calculated by $a=(0.5F_{\mathrm{geo}}\lambda/\pi)[(1.62/w_{\mathrm{pb3}})+(2.22/w_{\mathrm{pb6}})]$ equal to 26.67mm. Calculated by $\beta=arcsin(a/F_{\mathrm{geo}})$, the focus half-angle is 20.9°, and the effective area obtained from $A=2\pi F_{\mathrm{geo}}{}^2$ (1-cosβ) is $2.35\times10^{-3}\mathrm{m}^2$ where F_{geo} is the geometric focal length, i.e. radius of curvature of the radiation surface R, λ is the wavelength.

The transducer and the reflector are arranged in the water tank as shown in Figure 2. The power amplifier used is ELECTRONICS & INNOVATION MODEL: 1020L. The current monitor is Current Monitor 411 (Beatson Electronics, INC U.S.A.). The oscilloscope is Agilent DSO-X2002A. Adjust the transducer's position making the distance to reflector equal to F_{geo} and azimuth, elevation to maximize the first echo amplitude received. The three-way switch was placed on ② to measure the exciting voltage amplitude U_{T}, the first echo voltage amplitude U_1, exciting current amplitude I_T and the first echo current amplitude I_{echo}. The exciting voltage and working frequency of the transducer remained constant, then put this switch on ① to measure the open-circuit voltage amplitude of the power amplifier U_0.

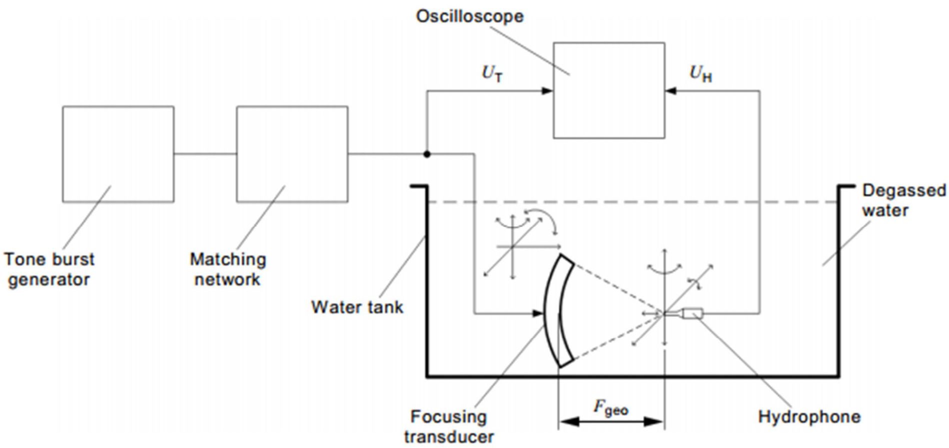

Figure 1. *Scheme of the measurement apparatus for determining the effective half-aperture of a transducer* [5].

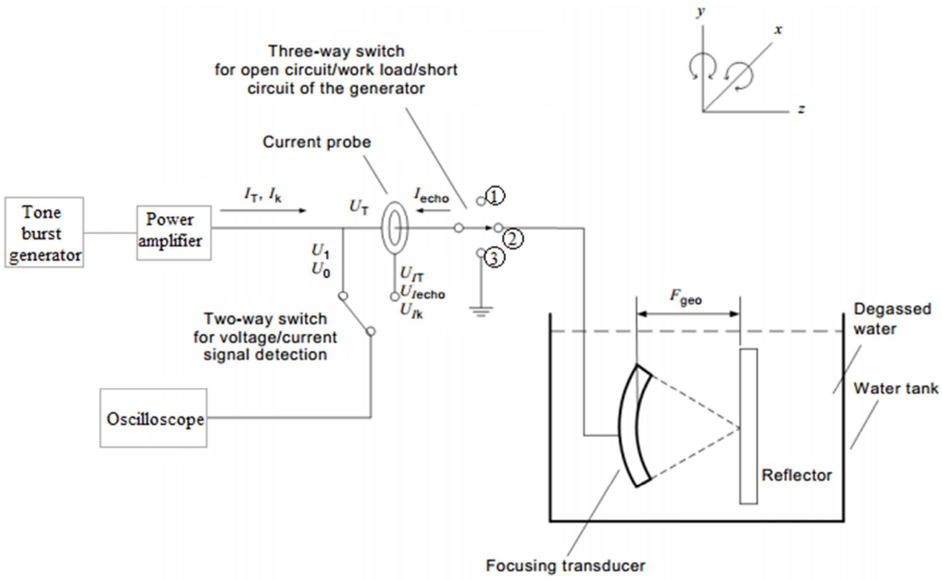

Figure 2. *Scheme of free-field self-reciprocity system applied to a spherically curved transducer* [2].

The maximum transmitting response at geometric focus to voltage is given by [5]

$$S_{vf} = \frac{p_f}{U_T} = kh\sqrt{\frac{\rho c U_{orms} I_{echorms}}{A r_{av} G_{sf} U_T^2}} \quad (1)$$

$$p_f = kh\sqrt{\frac{\rho c U_{orms} I_{echorms}}{A r_{av} G_{sf}}}\, e^{\alpha R} \quad (2)$$

where, p_f is the acoustic pressure at the geometric focus, $k = 2\pi/\lambda$ is circular wave number, h=R (1-cosβ) is the height at the center of the spherical segment, $r_{av}(\beta)$ is the average amplitude reflection coefficient on the reflector for the spherically curved transducer and its value is 0.928, G_{sf} is the diffraction correction coefficient of the spherically curved transducer and $G_{sf} = 0.886$, ρ, c is the mass density and acoustic velocity of water respectively. α is the acoustic attenuation coefficient in water, the acoustic attenuation $e^{\alpha R}$ for 1MHz ultrasound and distance R=75 mm in water can be ignored.

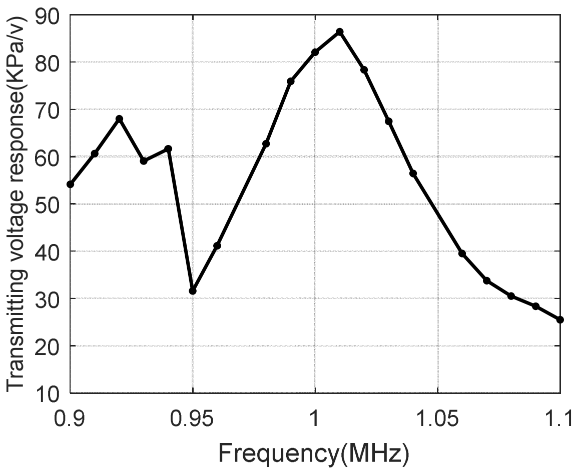

Figure 3. *The frequency response curve of the transmitting voltage response S_{vf} at the geometric focus of the transducer PA885.*

The curves of the transmitting voltage response S_{vf} at the geometric focus of the transducer vs frequency is shown in Figure 3, the maximum value of S_{vf} at 1.01MHz is 85.8 kPa/V.

2.2. Nonlinear Distortion of Ultrasound at the Transducer Focus

Calculating the local distortion parameter σ_q to determine nonlinear distortion of ultrasound at the transducer focus [16].

$$\sigma_q = z p_m \frac{2\pi f_{awf}\beta}{\rho c^3}\frac{1}{\sqrt{F_a}} \quad (3)$$

where z is the axial distance of the point of interest to the transducer face, i.e. the geometric focal length F_{geo}; p_m is the mean-peak acoustic pressure at the point in the acoustic field corresponding to the spatial-peak temporal-peak acoustic pressure; β is the nonlinearity parameter (β=1+B/A=3.5 for pure water at 20°C), f_{awf} is the acoustic-working frequency; F_a is the local area factor, $F_a = \sqrt{0.69A_{SAeff}/A_{b,-6dB}}$, A_{SAeff} is the source aperture area, i.e. the effective area of the transducer; $A_{b,-6dB}$ is beam area at the -6dB level. Figure 4 shows the relationship between the focal acoustic pressure p_f and the effective exciting voltage U_{Trms} of the transducer at 1MHz. In this figure, when the effective exciting voltage $U_{Trms} = 42.29V$, the focal acoustic pressure p_f is 3.58MPa, $\sigma_q = 0.46 (< 0.5)$, and the focal acoustic pressure caused by nonlinear distortion effect differs by less than 5% from the value in the absence of nonlinear effect. If 0.5 < σ_q < 1.5, this difference is between 5% and 25%. When $U_{Trms} = 65.25V$, p_f = 5.58MPa and σ_q=0.72 the acoustic pressure waveform at focal point appears obvious distortion with the estimated pressure deviation about 10% caused by nonlinearity, but the relation of focal pressure and exciting voltage remains good linearity as shown in Figure 4 and that of acoustic power and exciting voltage squared is also linear, see Figure 5.

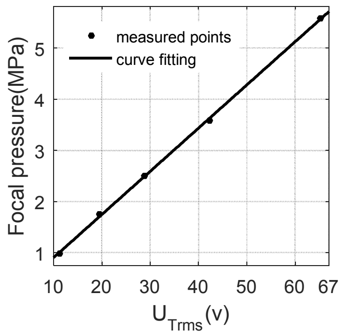

Figure 4. *The fitting line of the focal acoustic pressure p_f vs. the effective exciting voltage U_{Trms} of the transducer at 1MHz frequency.*

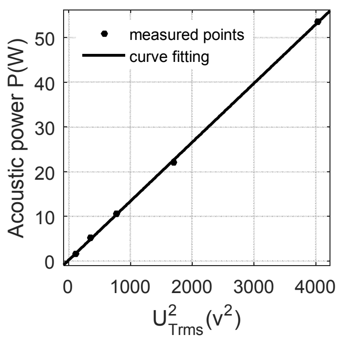

Figure 5. *The fitting line of output power P vs. exciting voltage squared U^2_{Trms}.*

3. Hydrophone Calibration

3.1. The Correction Coefficient for the Spatial Average Effect of the Acoustic Pressure over the Hydrophone Surface if the Hydrophone were Removed

The acoustic pressure received by the hydrophone is not the value at the geometric focus in free field, but the average acoustic pressure over the hydrophone surface if it were removed, which affects the sensitivity of the hydrophone to a certain extent, so it needs to be corrected. The correction factor of the pressure average effect of hydrophone G_2 can be derived:

$$G_2 = \frac{\overline{p_H}}{p_f} = 2cot^2\psi_m \int_0^{\psi_m} jinc(ka\ sin\psi)tan\psi sec^2\psi d\psi \quad (4)$$

where

$$\overline{p_H} = \frac{p_f}{A_m}\int_0^{\psi_m} jinc(ka\ sin\psi)\mathrm{dA}$$

$$dA = 2\pi R^2 tan\psi\ d(tan\psi)$$

$$A_m = \pi R^2 tan^2\psi_m$$

$\overline{p_H}$ is the average free-field pressure over the effective area of the active element of the hydrophone in the middle of the geometric focal plane if the hydrophone were removed. $\psi_\mathrm{m} = arc\sin(a_H/R)$ is the half-aperture angle of the hydrophone for the center of the focusing transducer. a_H is the effective radius of the active element of the hydrophone.

Obviously, G_2 is the function of parameters ka and ψ_m, the dependence of G_2 on ψ_m at several values of ka was shown in Figure 6. The values of function $G_2(ka, \psi_\mathrm{m})$ were list in Table 1, when the parameters ka and ψ_m in the table are close to the corresponding values of the measured transducers, G_2 can be obtained by linear interpolation using the data in the Table 1.

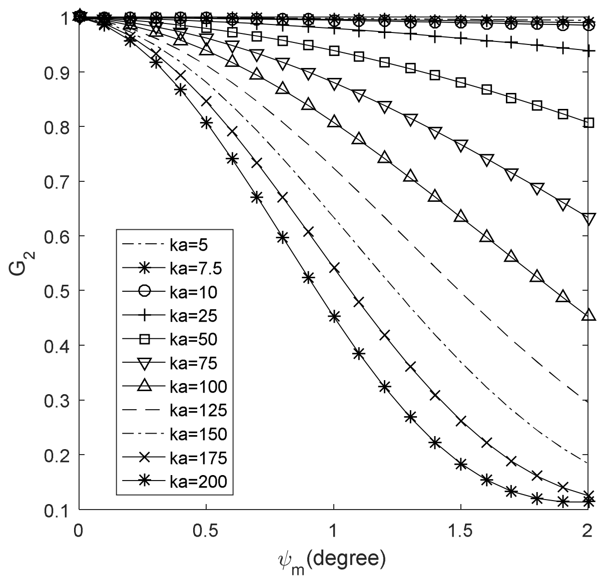

Figure 6. *Relationship of G_2 and ψ_m at several values of ka.*

Table 1. *The values of correction coefficient $G_2(ka, \psi_m)$ for the spatial average effect of the free-field acoustic pressure over the hydrophone surface if it were removed.*

ψ_m (°) *ka*	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2
5	1	0.9998	0.9996	0.9994	0.9991	0.9989	0.9986	0.9984	0.9981	0.9978	0.9975	0.9972	0.9969	0.9966	0.9963	0.9959	0.9956	0.9952	0.9948	0.9945	0.9941
7.5	1	0.9997	0.9994	0.9990	0.9987	0.9983	0.9979	0.9974	0.9970	0.9965	0.9960	0.9955	0.9950	0.9944	0.9938	0.9932	0.9926	0.992	0.9913	0.9907	0.9900
10	1	0.9996	0.9991	0.9987	0.9981	0.9976	0.9970	0.9964	0.9957	0.9950	0.9943	0.9935	0.9927	0.9919	0.9910	0.9901	0.9892	0.9882	0.9872	0.9861	0.9850
25	1	0.9989	0.9976	0.9961	0.9943	0.9924	0.9902	0.9879	0.9853	0.9825	0.9795	0.9763	0.9729	0.9693	0.9655	0.9615	0.9574	0.953	0.9484	0.9437	0.9388
50	1	0.9976	0.9944	0.9903	0.9853	0.9796	0.9730	0.9656	0.9575	0.9486	0.9389	0.9286	0.9175	0.9058	0.8935	0.8805	0.8670	0.8529	0.8382	0.8231	0.8075
75	1	0.9961	0.9903	0.9826	0.9730	0.9617	0.9486	0.9339	0.9176	0.8998	0.8806	0.8601	0.8383	0.8155	0.7916	0.7669	0.7414	0.7152	0.6885	0.6614	0.6341
100	1	0.9944	0.9853	0.9730	0.9575	0.9390	0.9176	0.8936	0.8671	0.8384	0.8077	0.7753	0.7414	0.7064	0.6706	0.6341	0.5973	0.5605	0.5240	0.4879	0.4527
125	1	0.9924	0.9796	0.9617	0.9390	0.9119	0.8806	0.8457	0.8077	0.7669	0.7241	0.6796	0.6341	0.5881	0.5422	0.4969	0.4527	0.4100	0.3693	0.3309	0.2952
150	1	0.9903	0.973	0.9486	0.9176	0.8806	0.8384	0.7917	0.7415	0.6886	0.6341	0.5789	0.5240	0.4702	0.4184	0.3693	0.3235	0.2817	0.2443	0.2115	0.1836
175	1	0.9879	0.9657	0.9339	0.8936	0.8458	0.7917	0.7328	0.6706	0.6066	0.5422	0.4791	0.4184	0.3614	0.3091	0.2624	0.2219	0.1879	0.1605	0.1398	0.1253
200	1	0.9853	0.9575	0.9176	0.8671	0.8077	0.7415	0.6706	0.5974	0.5240	0.4527	0.3853	0.3235	0.2688	0.2219	0.1836	0.1539	0.1328	0.1197	0.1136	0.1136

3.2. Hydrophone Calibration Experiment

Using the calibrated focusing transducer as an acoustic source, remove the flat reflector from the tank and place the hydrophone to be calibrated near the geometric focus, repeatedly adjust the position and direction of the hydrophone so that its maximum sensitivity direction is collinear with the beam axis of the focus transducer, and the distance between them remains F_{geo}, the cable-end loaded voltage amplitude E_{H} reaches maximum and read by the oscilloscope (Agilent DSO-X2002A, probe's electrical load: 10MΩ, 11pF).

The relationship between the root mean square (rms) excitation voltage U_{Trms} and the corresponding hydrophone rms cable-end output loaded voltage E_{Hrms} is shown in Figure 7, and the linearity is 5.36% by least squares fitting.

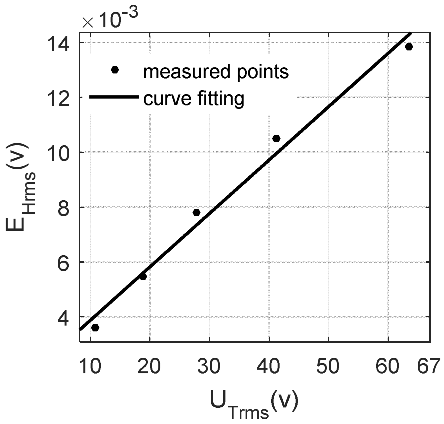

Figure 7. *The rms hydrophone cable-end loaded output voltage E_{Hrms} vs. the exciting voltage U_{Trms}.*

The focal intensity is $I_{\text{f}} = qp_{\text{f}}^2/(2\rho c)$, where q = (1+cos β)/2 is the cosine-function value of the phase difference between the particle velocity and the acoustic pressure at the geometric focus, i.e. the acoustic power factor [2]. Figure 8 is the relationship between the focal acoustic intensity and the rms excitation voltage.

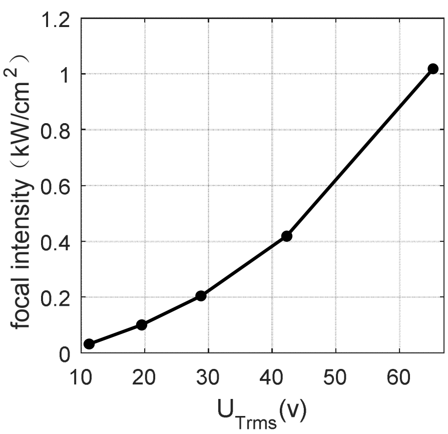

Figure 8. *The focal intensity vs. rms exciting voltage U_{Trms}.*

Figure 8 shows that the focal acoustic intensity increases with the square law when the excitation voltage increases. The focal acoustic intensity can reach 1.02W/cm^2 at p_{f} =5.58MPa.

The hydrophone was placed at the geometric focus, and the cable-end loaded output voltage of the hydrophone was measured. Then the free field cable-end loaded voltage sensitivity was given by

$$M_{\text{L}} = E_{\text{H}}/(p_{\text{f}} \cdot G_2) \quad (5)$$

The frequency response of the free field cable-end voltage sensitivity of the hydrophone is shown in Figure 9.

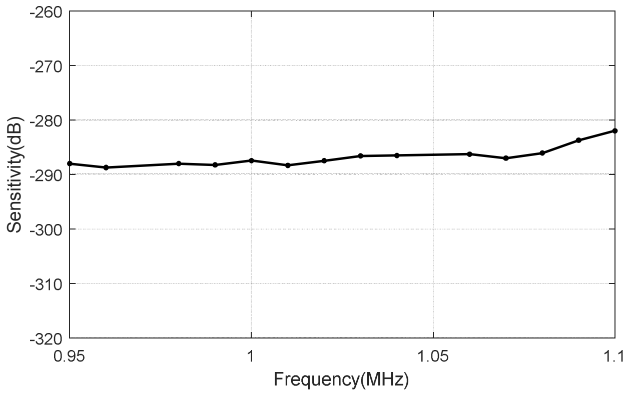

Figure 9. *The free field cable-end loaded voltage sensitivity level of hydrophone.*

From Figure 9, when the frequency is 1MHz, the free field cable-end loaded voltage sensitivity level of hydrophone is -287.5dB reference: 1V/μPa. In the frequency range 0.95MHz to 1.06MHz the frequency response of sensitivity is relatively flat within a range of ±1.33 dB.

4. Conclusion

A new calibration method for the hydrophone used for HIFU was presented and carried out, which is based on the self-reciprocity method of a high-pressure focusing transducers. The values of correction factor $G_2(ka, \psi_{\text{m}})$ for spatial average effect of pressure over the hydrophone surface were given. The acoustic pressure at the focal point calibrated by experiments can be up to 5.58MPa (1.02kW/cm^2), the calibration of the hydrophone used in HIFU field has been realized. The applications of fully degassed water and the burst source can effectively increase the cavitation threshold so that it did not happened in calibration. At normal temperature, the cavitation threshold of tap water is about -1MPa, and that of degassed water is about -30MPa. In the experiment the maximum pressure 5.58 MPa is much less than the threshold but has introduced 10% nonlinear change of the local field as $\sigma_{\text{m}} = 0.72 > 0.5$. It is obvious that the nonlinear distortion effect is the primary obstacle for increasing the maximum pressure in experiment. To increase the upper limit of local distortion paramete σ_{m} in experiment the acoustic source must be optimized. Reducing the geometric focal length, increasing the aperture and the local area factor of the transducer are the effect methods.

Acknowledgements

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References

[1] GB/T 32522-2016 Acoustics-Electroacoustic characteristics and measurements of piezoeletric focusing ultrasonic transducers (in Chinese) [S].

[2] IEC TS 62903 Ed. 1.0-2018 Ultrasonics – Measurements of electroacoustical parameters and acoustic output power of spherically curved transducers using the self-reciprocity method [S].

[3] W SHOU, J YAN, H WANG,. Free-field reciprocity calibration in a convergent spherical acoustic wave of a focusing transducer [J]. Chin. Phys. Lett., 19 (8): 1131-1136, 2002.

[4] S Duan, W Shou, and P He et al., “ A novel method to measure acoustic power of focusing transducer with spherical surface based on self-reciprocity theorem,” Chinese Physics Letters, 22 (1): 146-149, 2005.

[5] Shou W. D., Yu L. L., Duan S. M., et al, Research on electro-acoustic characteristics and measurements of spherically focusing transducer [J] (in Chinese), Technical Acoustics, 000 (005), 379-388, 2013.

[6] G Z Xing, P Yang, W D Shou, M Wang, X J Feng, L B He, Hydrophone reciprocity calibration in spherically focused ultrasonic field from 1 MHz to 15 MHz [J], Acta Acustica united with Acustica, 105: 273-283, 2019.

[7] GB/T 19890-2005 Acoustics- Measurements of acoustic power and field characteristics of high intensity focused ultrasound (HIFU), (in Chinese) [S].

[8] Shaw A, tea Haar Gail, NPL REPORT DQL AC-015: Requirements for Measurement Standards in High Intensity Focused Ultrasound (HIFU) Fields, 2006. [S].

[9] IEC REPORT 62649-2010: Ultrasonics-Requirements for Measurement Standard of High Intensity Therapeutic Ultrasound (FITU) Equipments. [S].

[10] Granz B. PVDF hydrophone for the measurement of shock waves [J], International Symposium on Electrets. IEEE, 1988.

[11] Robinson S, Preston R. PVDF reference hydrophone development in the UK-from fabrication and lamination to use as secondary standards [J]. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 47 (6): P. 1336-1344, 2000.

[12] L Li, The study of hydrophone for the measurement of High intensity focused ultrasound and calibration techniques, (Academic dissertation for MA. Eng in SJTU, China) 2003.

[13] Gélat, Pierre, Shaw, A. Relationship between acoustic power and acoustic radiationforce on absorbing and reflecting targets for spherically focusing radiators [J]. Ultrasound Med Biol, 41 (3): 832-844, 2015.

[14] Shou W, Huang X, Duan S, et al., Acoustic power measurement of high intensity focused ultrasound in medicine based on radiation force [J]. Ultrasonics, 44 (8): e17-e20, 2006.

[15] Shou W, Recall HIFU measurement and talk about standard innovation [J] (in Chinese), International Medical Devices, 17 (2): 70-74, 2011.

[16] IEC62127-1: 2013 Ultrasonics- Hydrophones- Prat1: Measurement and characteristics of medical ultrasonic fields up to 40 MHz. [S].