Visualization and Image Processing Techniques in the Evaluation of Ultrasonic Equipment Radiation Intensity

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Abstract. A method for evaluating the intensity of ultrasonic medical equipment radiation is presented in the paper. The capabilities of image processing of equilibrium gas bubbles under influence of acoustic field in fluid are described to determine the bubble radius and subsequently evaluate the ultrasonic radiation intensity.

Keywords: Bubble, ultrasound radiation intensity, image processing, ImageJ, iPython Notebook

INTRODUCTION

The use of ultrasonic (US) radiation in various fields of medicine (diagnostics, therapy, surgery, cosmetology) is largely determined by its intensity. Maximum permissible levels of US radiation intensity for each application are strictly regulated by international and Russian standards in order to avoid the negative effects of US treatment (thermal and mechanical effects). For example, according to the FDA [1] in US diagnostics the intensity $I < 720$ mW/cm^2, in US therapy (IEC 601-2-5-84) – $I < 1.2$ W/cm^2. Therefore, used in medical applications US equipment requires periodic calibration of its basic parameters, in particular, the radiation intensity.

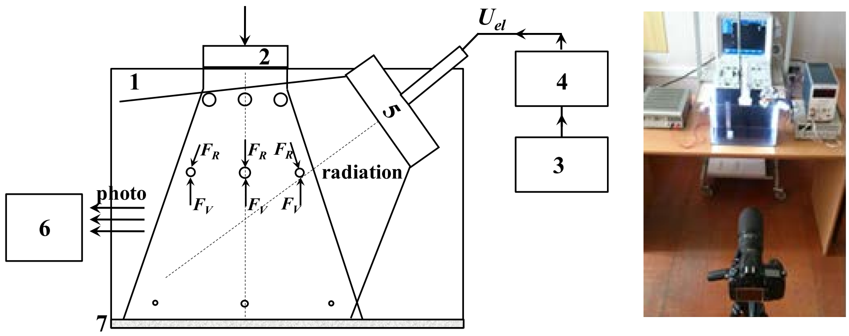
Among different methods of measuring the US radiation intensity (calorimetric, interferometric, method of reciprocity [2]), the most common and available method is the measurement of radiation pressure. However, its existing implementations are generally applicable only for continuous radiation and do not allow to evaluate the intensity distribution in space.

The authors proposed a method for estimating the US radiation intensity and its spatial distribution and visualization of acoustic field and its orientation, based on the method of gravitational balancing the force of US waves radiation pressure and the buoyant force, acting on a gas bubble of a certain size [3]. Analyzing the equilibrium size of bubbles in a fluid in the US field makes it possible to evaluate the intensity and visualize its distribution at any point in space.

An air bubble in the fluid (water) can be represented in form of a compressible sphere, whose density ρ is much smaller than the density ρ_0 of the fluid: $\rho \ll \rho_0$. According to proposed physical model of US radiation interaction with air bubbles in a fluid [4], the bubbles are under influence of radiation pressure force, buoyant force, radiation pressure force of scattered wave. Furthermore, a gas bubble in a fluid, while in the US field, performs radial oscillations, acting as a secondary source and interacting with particles around it, including other bubbles. These oscillations in US field cause non-uniform motion of the fluid near bubbles, leading to the bubbles attraction in perpendicular to US waves propagation direction and the bubbles repulsion along the US field [5]. As a result of attraction force acting between bubbles, the bubbles approach each other deviating from their spherical shape.

Interaction effects stated lead to unstable behavior of bubbles in US field and appearance of artifacts in obtained images, which requires the development of new approaches to obtained images analysis and improvement of precision in inhomogeneities size evaluations.

EXPERIMENTAL SETUP FOR ULTRASONIC RADIATION INTENSITY EVALUATION



(a) (b)

Figure 1. Block-scheme (a) and photo (b) of US transducer parameters evaluation setup: 1 – container with a fluid; 2 – investigated US transducer; 3 – sinusoidal signals generator; 4 – adjustable amplifier; 5 – bubbles generator; 6 – photography device; 7 – absorber

Scheme and photo of the experimental setup for the US radiation intensity evaluation and its distribution in space is presented in Fig. 1. Near the surface of container 1 with a transparent wall there are the investigated US emitting transducer 2, radiating into the fluid the wave normal to the surface, and a specialized low-frequency US transducer 5 that emits the US wave at an angle to the surface, acting as a gas bubbles generator. Formation of bubbles occurs by supplying the low frequency transducer from the sinusoidal signals generator 3 through an adjustable amplifier 4 with electrical voltage corresponding to the threshold level of stable cavitation [3]. The investigated US emitting transducer 2 at the operating frequency forms in the fluid an acoustic field with radiation intensity *I*, at the same time the superposition of bubbles generator and investigated emitting transducer fields is visualized. After shutting-down the bubbles generator, some bubbles of larger size float to the surface due to excess of the buoyant force over the radiation pressure force. Part of smaller sized bubbles moves in the opposite direction due to the excess of radiation pressure force over the buoyant force, gathering near the bottom surface. Bubbles with dimensions corresponding to the equilibrium condition (equality of buoyant and radiation pressure forces) are distributed in space according to intensity values in the transducer acoustic field. Distribution pattern formed of equilibrium state bubbles is recorded by the photography device 6. The registered photographic image is processed using a specialized software, allowing the bubble radius *r* measurement at any point of interest in the plane of photographic image [3]. Evaluation of US radiation intensity is produced in accordance with the developed physical model of US radiation interaction with air bubbles in the fluid.

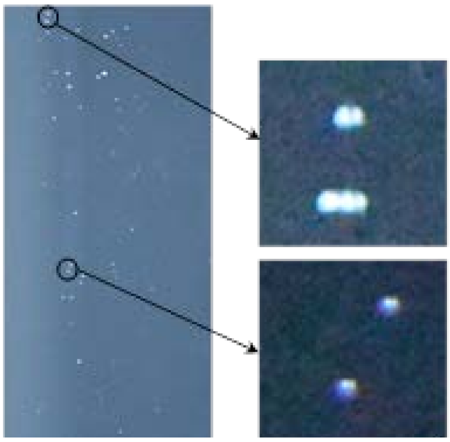


Figure 2. An example of equilibrium gas bubbles distribution recorded

To improve the quality of the resulting image and its resolution to increase the equilibrium gas bubbles size estimates precision, minimize error and improve the reliability of US radiation intensity evaluation, the conditions of the visualization and registration process are optimized.

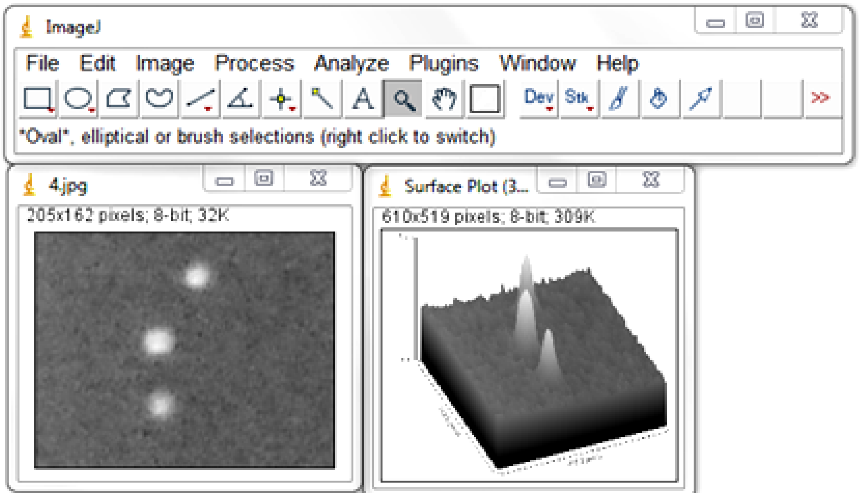
It is recommended to use a full-frame photographic camera like Nikon D800 Body with resolution of not less than 36 megapixels, CMOS image sensor size 35.9x24.0 mm and a macro lens like 200mm f/4D ED-IF AF Micro-Nikkor with the following settings: manual lens focus, the minimum exposure (1/4000 s or faster), maximum ISO sensitivity (“Hi 1” mode) with noise suppression and automatic distortion control, manual white balance settings or white balance in direct sunlight mode. Higher stability and uniformity of generated bubbles size and reduced influence of artifacts on the image is also achieved through the use of 1.2 % glycerin solution in distilled water at a temperature of 30 °C ÷ 40 °C as the fluid to form bubbles. Fig. 2 illustrates the received equilibrium gas bubbles spatial distribution image and the enlarged view of individual bubbles.

Image Processing Methods

The recorded images are subject to significant influence of artifacts caused by oscillating bubbles, deviations from the spherical shape during the approach of two bubbles, as well as distortions caused by photographing through a glass. Artifacts distort the initial information on the geometrical dimensions of the bubbles. The image processing software methods developed include localization and identification of bubbles, coupled bubbles detection, bubble boundaries delineation and size estimation, building the dependencies of the bubble size on observation point parameters. For detuning from artifacts, extracting the information about size of bubbles and subsequent analysis, the possibilities of various image processing methods are investigated.

Today, the use of computer technology for scientific data analysis is an accepted fact [6]. There are various software tools containing a lot of ready-made algorithms and methods for image processing. The open source software ImageJ [7] possesses significant set of ready-made algorithms as well as the ability to extend the functionality by implementing the necessary methods using embedded macro language or subroutines (plug-ins) written in Java. A grayscale image example of bubbles (a) and values of pixels intensity in three-dimensional space (b) in the ImageJ software are presented in Fig. 3.

For the tasks of bubbles localization in the image and their radius calculation the following algorithm is applied. The grayscale image is considered as a two-dimensional matrix of pixels, the values of which characterizes the color intensity of the corresponding picture element. The bubbles localization task is the identification of a pixel belonging to image background or bubble. The identification difficulty lies in the variability of background intensity values (Fig. 4, a). The exception of variability is achieved by applying a local threshold filter on the image areas of a size corresponding to the size of bubble. The result of this filter applying are selected areas of bubbles.



(a) (b)

Figure 3. Image of bubbles in grayscale (a) and pixel intensity values in three-dimensional space (b) in open source software ImageJ

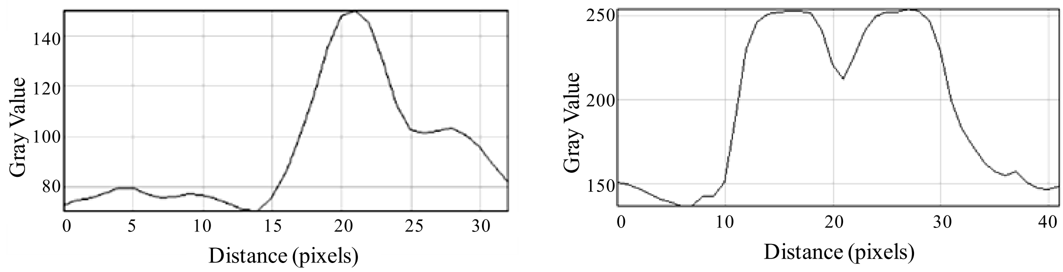
To determine the coupled bubbles radius (Fig. 4, b) the following algorithms can be used:

– approximation of the selected bubble using an ellipse and calculation of its equivalent radius, considering the equality of the ellipse area and the circle area (Fig. 5, a);

– calculation of the radius as the arithmetic mean of ellipse semi-axes *a* and *b* (Fig. 5, b);

– calculation of the radius as half of the bubble maximum size on the *X* axis.

The effectiveness of algorithms mentioned was evaluated on the basis of the standard deviation of measured radii from the calculated ones according to known data about the US radiation intensity and bubble sizes according to the physical model of US waves interaction with bubbles.



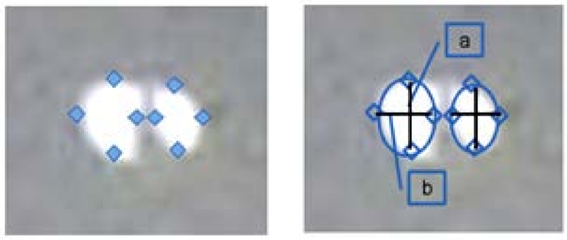
(a) (b)

Figure 4. Graphs of intensity values of pixels with non-uniform background (a) and with the effect of coupled bubbles (b)

When processing the experimental images obtained with variable shooting conditions the ImageJ program showed the less practical efficiency in comparison to other image processing tools. Less efficiency lies in the fact that any changes in algorithm lead to necessity of making changes in subroutine (plug-in) code and subsequent compilation, which significantly increases processing time.

In such conditions, greater effectiveness has been shown by iPython Notebook software (Fig. 6, a), which is an interactive shell for the Python language [8]. Interactivity allows to observe the result of algorithm changes without recompiling the program.

Unlike localization by identifying the pixels belonging to background or bubble using a threshold filter, another localization method is based on determining the local maxima of



(a) (b)

Figure 5. Bubble radius calculation technique

bubbles intensity values. The algorithm in iPython Notebook with new approach application includes the following steps:

1. Read the image (Fig. 6, a).

2. Selection of local area and conversion the color model of image to grayscale (Fig. 6, b). One of the most common problems in image processing is the presence of noise, which is mostly a variation of intensity and inhomogeneity of the background. To exclude noise and inhomogeneity the median and threshold filters are applied. The median filter eliminates the noise, the threshold filter divides image pixels in belonging to background or bubble by intensity. These filters are applied using the “sliding window”, which size corresponds to desired bubble average size.

3. Determining the local maxima using the “sliding window” technique (Fig. 7, a).

4. Calculation of bubble radii using the approximation of bubble shape as an ellipse, considering the equality of ellipse and circle areas, and forming the result tables by depth (Fig. 7, b).

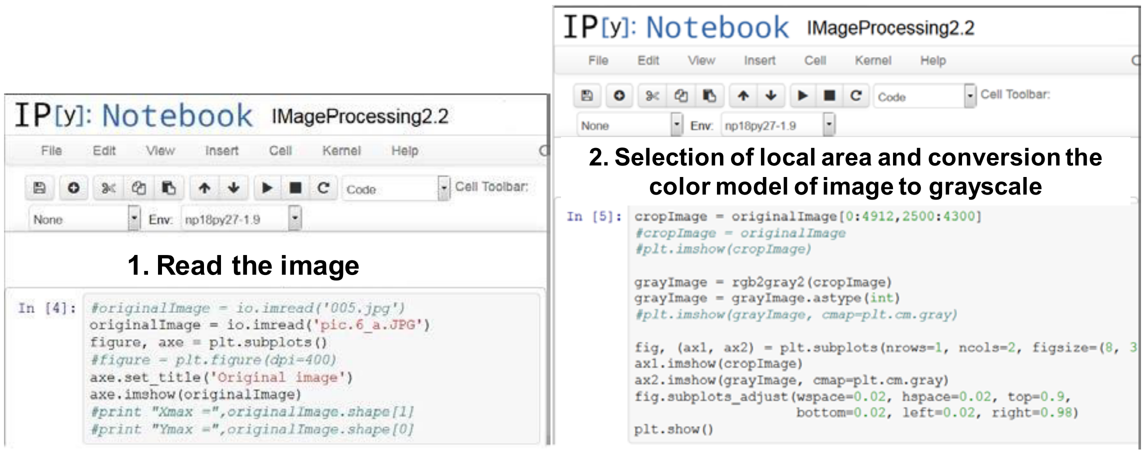
The image processing result obtained with use of the algorithm specified above is presented in Fig. 8.

The deviations of the bubbles radii from the mean values at a given depth are 6÷12 μm (8÷15 %).

At the same time, with the increase in distance there is a decreasing in radii and their evaluation accuracy.

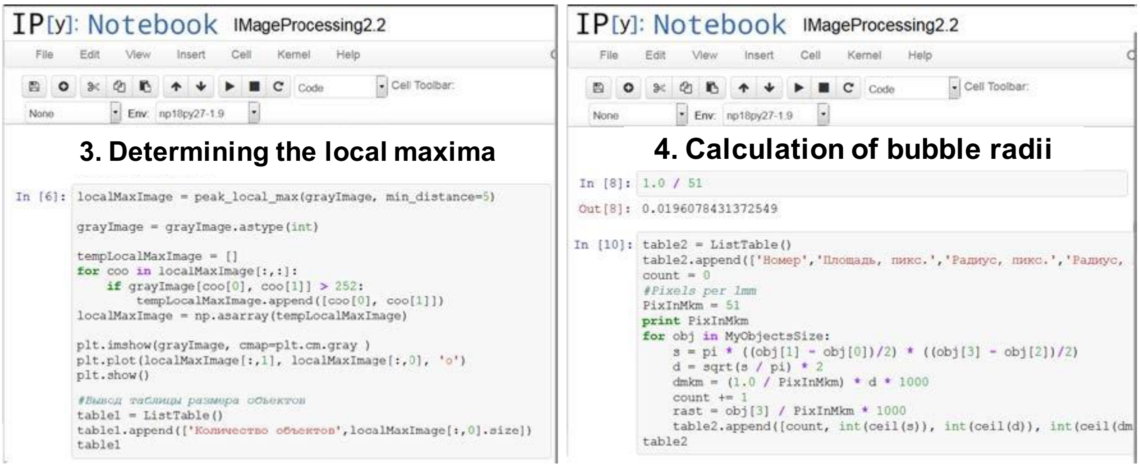
The bubbles image processing results are the equilibrium bubbles radius values in point of interest. Knowing the latter, it is possible to determine the US radiation intensity in accordance with the expression:

$$I = \frac{\rho_0 C_0 g \left((kr)^6 + \left[\frac{3\mu^2}{\delta} - (kr)^2 \right]^2 \right)}{3k^4 r^3}, \quad (1)$$



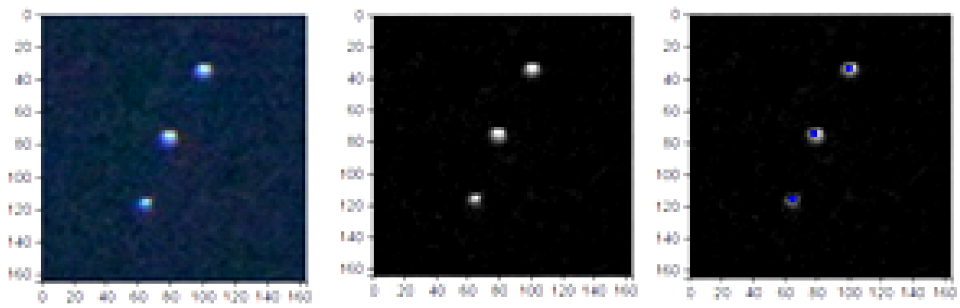
(a) (b)

Figure 6. An example of image processing in iPython Notebook software: step 1: read the image (a); step 2: the selection of area to process and grayscale conversion (b)



(a) (b)

Figure 7. An example of image processing in iPython Notebook software: step 3: determining the local maxima (a); step 4: calculation the results (b)



(a) (b) (c)

Figure 8. Original image (a), grayscale image (b), image with localized bubbles (c)

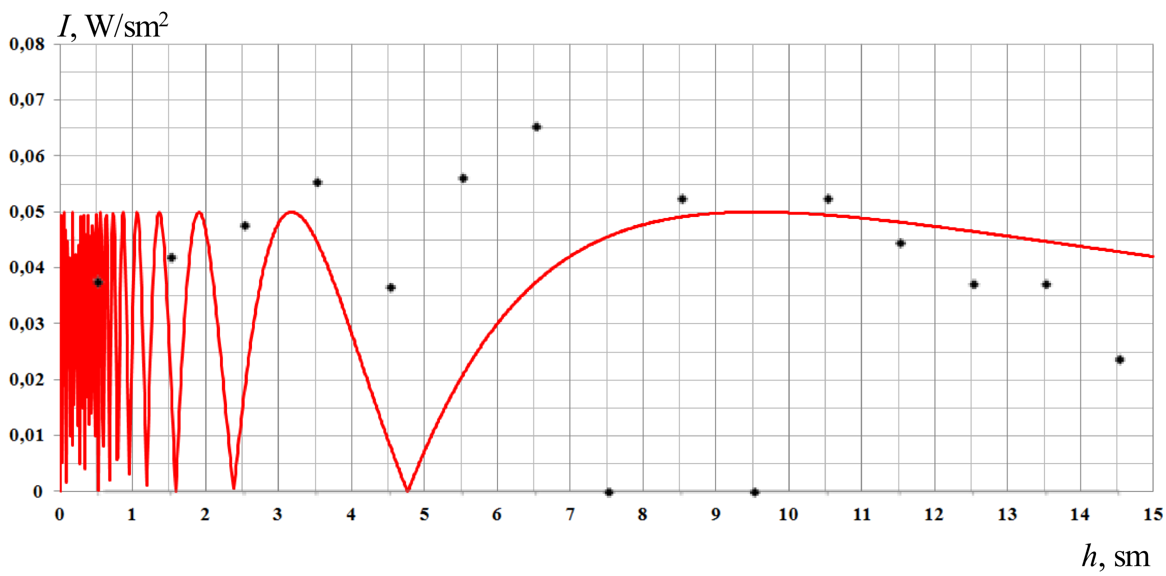


Figure 9. The result of US therapeutic apparatus UST 1.01F intensity evaluation

where r is the radius of a gas bubble in a state of equilibrium; $\delta = \rho_0/\rho$, ρ_0 is the water density, ρ is the bubble density; k is the wave number; $\mu = C/C_0$, C is the sound velocity in a bubble; C_0 is the sound velocity in water.

The developed method, device and software are tested to evaluate the intensity of US therapeutic apparatus UST 1.01F ($f = 880$ kHz) at $I = 0.05$ W/cm^2. The intensity evaluation result is shown in Fig. 9, where each point represents the result of experimental evaluation of US radiation intensity, solid line is a theoretical curve of the intensity distribution in depth. The deviation of experimental results from theoretical ones does not exceed 30 %, which corresponds to intensity tolerances according to the device passport data.

Thus, the paper proposes new approaches to image analysis of equilibrium gas bubbles in a fluid under influence of an acoustic field, and used for evaluation the ultrasonic radiation intensity of medical equipment. The algorithms developed allow to significantly reduce the effect of artifacts caused by unstable behavior of bubbles, geometry deviations, photography distortion, and to improve the bubble geometrical sizes evaluation accuracy. The correctness of image processing results is confirmed by the agreement of theoretical and experimental results of ultrasonic therapeutic equipment radiation intensity evaluation.

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