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# Optical holography in ultrasonic research

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## Introduction

The prehistorical period of optical method application in the research of ultrasonic vibrations is associated with vibrating surfaces amplitude measurement by laser methods [1, 2]. A developed by us modulation-photometric method [3] allowed us to eliminate the main disadvantage of the interferometric methods – sensitivity to external vibrations. Later we have developed new modifications of photometric method that might allow us to measure energetic parameters of pulse vibrations [4], to calibrate ultrasonic transducers [5], to measure acoustic pressure (ultrasonic intensity) at a desired ultrasonic field point by an optical light-guide probe [6,7]. Although the laser vibrations measurement methods are absolute and rather accurate, however in respect to informativeness, they are inferior to the optical holography methods, which allow to visualize, measure and investigate three-dimensional acoustic field in real time, including pulse mode [8,9].

## Application of holographic methods in ultrasonics research

In the Ultrasound science institute of Kaunas University of Technology such research works were carried out by us in the eightieth of the last century [10-12], and they enabled us to investigate not only sound range but also low frequency ultrasonic vibrations (tens of kHz). By classical repetitive exposition holographic interferential method, when a visualizing laser beam of rays diffusively reflects from the vibrating surface and interferes with a reference beam, there were obtained some qualitative images of small plates bending vibrations transducer (Fig. 1,a,b) [13,14], according to which there have been calculated spatial acoustic field pressure distribution three-dimensional images [15]. More complicated is the visualization of curvilinear vibrating surfaces vibrations and the calculation of an acoustic field [Fig.1,c].

Unfortunately, the repetitive exposition holographic method is effective only within the range of rather low ultrasonic frequencies when the surface vibrations amplitudes $\xi$ are longer than the optical wavelength $\lambda_o$ ($\xi \geq \lambda_o$). To visualize an acoustic field when there are higher ultrasonic frequencies diffraction methods may be used.

By the way, as light diffraction effectiveness is associated with the acoustic wavelength (with a diffraction lattice constant ), therefore particularly qualitative images may be obtained in the high ultrasonic frequencies range. If a simple shadow casting method gives an integral flat acoustic field image [16], then having used a shadow casting and holographic methods combination in pulse mode, we have obtained a spatial (holographic) image of a single ultrasonic pulse (Fig. 2) [10].

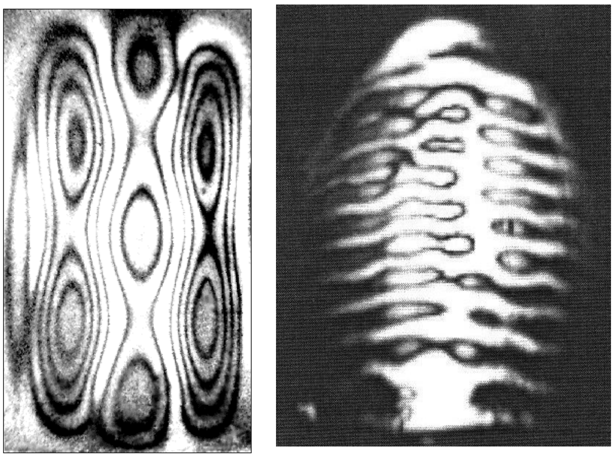

a) b)

Fig.1. **Holographic interferograms of vibrating by bending vibrations plates surfaces: a) bending vibrations transducer (*f*=30kHz); b) stream-line shape thin-walled shell radiator (*f*=43.3kHz)**

Unfortunately, effectiveness of a light diffraction depends not only upon the holographing pulse spectrum, but also upon its length, therefore to register short (half-wave length) ultrasonic pulses there are needed especially powerful laser pulses (pulse energy $W \cong 0.5$ mJ; duration $\cong 3 \cdot 10^{-8}$s). It is natural that such investigations are rather complex and expensive.

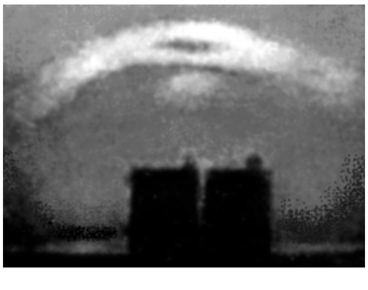
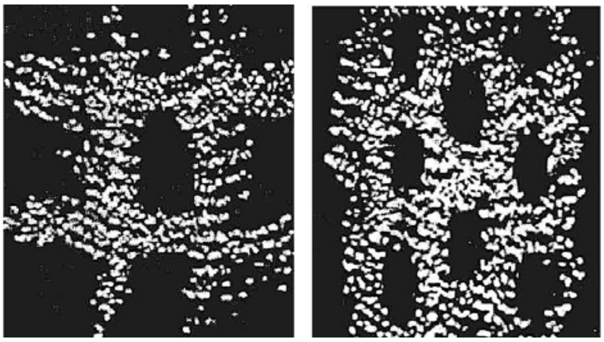


Fig. 2. **Holographic image of a single ultrasonic pulse ($\tau_i$ = 5 μs)**

Ultrasonic vibrations of an object in a real time may be investigated in a holographic system in which on a way of an objective ray there is placed a hologram of a non-vibrating investigated object. However in this case, optic distances (and also geometric) must be kept constant within optic accuracy. Due to this fact the investigations may be carried out only in a laboratory, isolating the tests stand from vibrations. This disadvantage is not characteristic for holographic interferential method of granular structures (speckle holography) [17], when the hologram of a rough surface is registered by a video camera (Fig. 3). In this case on the screen of a monitor one may observe various vibrations modes of a transducer when changing excitation frequency.



a b

Fig.3. **Holographic interferograms of bimorph piezoelectric transducer vibrations modes on the monitor screen. Resonant frequencies of the vibration modes: a - *f*=30kHz; b - *f*= 74.5 kHz (the interferograms have been registered by V. Minialga)**

An important disadvantage of the speckle structures of holographic interferometry is in its nature - the image of vibrations distribution is granular and thus is not distinct enough. Sometimes image quality may be improved by using digital filtering, however, in this case information amount is not increased.

## Method of liquid surface relief holographing

The optical holography methods are particularly useful in measuring ultrasonic energetic characteristics – radiation pressure, intensity and also for measuring a liquid surface relief [18, 19]. The essence of the method is the investigation of the liquid surface relief, formed on the liquid surface, when acting it by ultrasonics wave. Under the ultrasonic influence the radiation pressure $\Pi\ (x,y)$ (Fig.4) deforms a liquid surface it, and for ideal liquid, the viscosity factor of which $\gamma\ = 0$, the deformation is given by:

$$\xi(x,y)=\frac{\Pi(x,y)}{g\rho}=\frac{2J(x,y)}{g\rho\, c}=\frac{P^2(x,y)}{gp^2c^2} \qquad (1)$$

where $g$ is the free fall acceleration factor, $\rho$ is the liquid density, $c$ is the sound velocity in the liquid, $P(x,y)$ is the vibrating pressure amplitude, $x,y$ are the coordinates in liquid (Fig. 5).

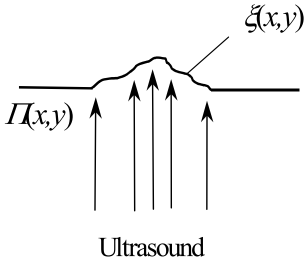


Fig.4. **Liquid surface deformation by an acoustic radiative pressure**

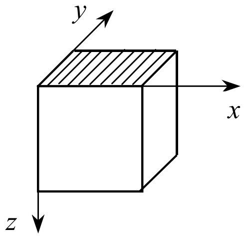


Fig. 5. **A volumetric element of a liquid surface**

For real liquids acoustic radiation pressure is given by:

$$\Pi(x,y)=g\rho\xi(x,y)-\gamma\left[\frac{\partial^2\xi(x,y)}{\partial x^2}+\frac{\partial^2\xi(x,y)}{\partial y^2}\right]. \qquad (2)$$

It is obvious that in order to calculate the acoustic radiation pressure of an acoustic field, it should be enough to measure a liquid surface relief $\xi=\xi(x,y)$. For this purpose there is pulse surface holography used. On the same photographic plate two holograms are registered: when the liquid surface is not acted upon by acoustic radiation pressure and when the liquid surface is deformed by an acoustic pressure. The time interval between these two expositions is defined by duration of a liquid surface transient response. The calculated water surface transient response [20] is shown in Fig. 6. From the calculation results follows that for holographing a water surface the time interval between laser pulses, should be T> 260 μs.

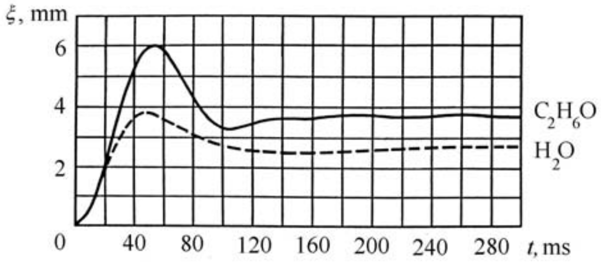


Fig. 6. **Theoretical liquid surface transient characteristics**

In order to make a holograph of a liquid surface relief, there is used an arrangement, the schematic diagram of which is shown in Fig.7 [11]. The light beam of the pulse laser $IL_1$ is used to register the hologram of a liquid surface, undeformed by ultrasonic field. For this purpose a beam is directed by a beam splitter SD onto the liquid surface, reflecting from which it lights up a holographic photographic plate HF. Upon the plate also falls a reference beam flow, reflected from the mirror S. After registering the first hologram, a synchronization unit switches on a high frequency generator, which excites the ultrasonic emitter UE. When a stable liquid surface relief has been formed, the synchronization unit switches on the pulse laser $PL_2$, and by means of its pulse a lliquid surface relief hologram on the same photographic HF plate is registered.

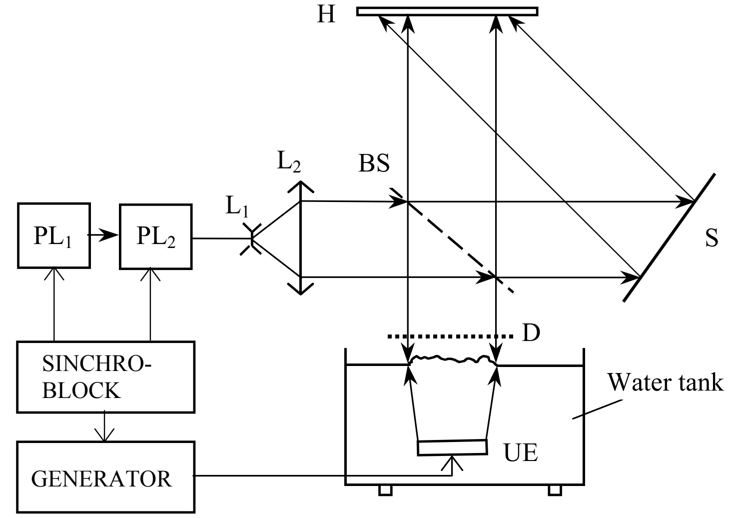


Fig. 7. **Schematic diagram of pulse holography of ultrasonic radiator acoustic field: PL$_1$, PL$_2$ – pulse ruby lasers (wavelength $\lambda$ = 694 nm); UE – ultrasonic emitter; L$_1$, L$_2$ – lenses; BS – beam splitter; D – light diffuser; S – mirror; H – holographic plate**

Having developed the hologram, in the light of He-Ne laser ($\lambda$ = 633 nm) an imaginary liquid relief image of $\xi(x,y)$ = const interferential isolines is observed, which are obtained in a space when there interfere two registered holograms.

Fig. 8 shows the hologram of a water surface relief, which is created by the double ultrasonic radiator excited by 0.24 ms duration 2.24 MHz pulses. The ultrasonic transducer is located at 120 mm distance from the surface, thus the registered acoustic field cross-sectionis in the Fraunhofer zone.

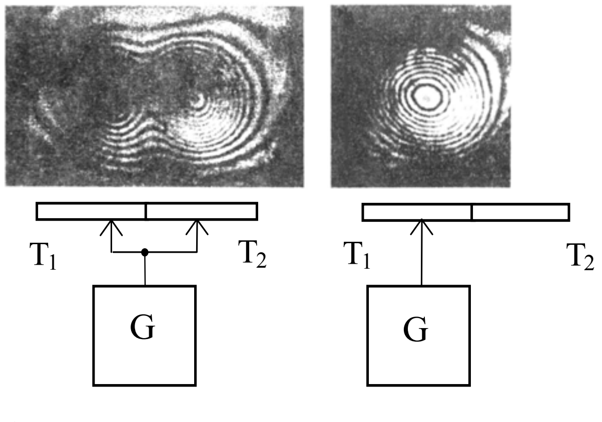


Fig. 8. **Acoustic field holograms of a double ultrasonic transducer [21]**

The height of the liquid relief is calculated by

$$\xi(x,y)=\frac{m\lambda(\cos\theta_1+\cos\theta_2)}{4} \qquad (3)$$

where $m$ = 1, 2… are the numbers of interferential lines, $\lambda$ is the wavelength of a pulse laser light, $\theta_1$ and $\theta_2$ incidence and reflection angles of the light beam. The method of two expositions surface relief holography allows to assess qualitatively ultrasonic field parameters. This method was used in investigation of liquid surface relief formation peculiarities, caused by impulsive ultrasonic waves and for the performance of the ultrasonic intensity calculations, evaluating the tension of a liquid surface.

## Calculation of ultrasonic radiator field

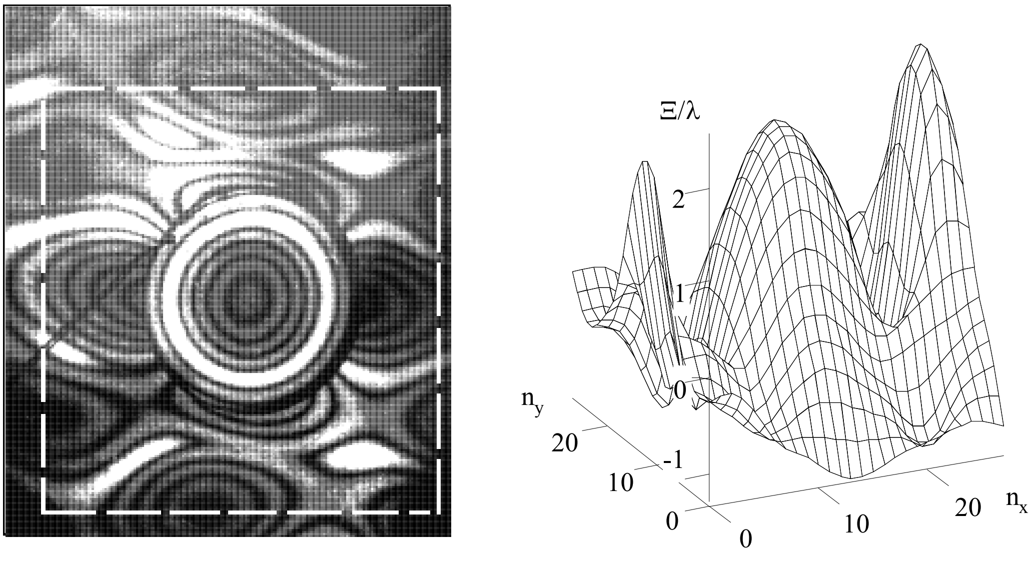
According to the registered surface holographic interferograms of an ultrasonic transducer it is possible to calculate the acoustic field, directivity patterns, and to perform computer simulation of an acoustic field [13, 22, 23]. Fig. 9 illustrates vibration distribution of a sophisticated bimorph radiator surface, registered by the method of two expositions holography and the calculated three-dimensional image of this distribution.

The scalar potential $\varphi$ of an acoustic field is calculated by the surface integral method [16]. In a discrete case $\varphi$ is calculated using the formula:

$$\varphi_{lm}=\sum_j\sum_k\left\|V_{ij}\right\|\frac{e^{ikr_{jklm}}}{r_{jklm}}, \qquad (4)$$

where $\left\|V_{jk}\right\|$ is the matrix of the vibrations amplitudes and phases distribution on the radiator surface, $k$=2$\pi$/$\Lambda$ is the wave number, $r_{jklm}$ is the distance between the points on the radiator surface and calculation plane, $\Lambda$ is the acoustic wave length.

Fig.10 shows a normalized directivity pattern of that ultrasonic transducer, surface vibration distribution of which is illustrated in Fig. 1a. The directivity pattern of this transducer possesses two main lobes and has minimal side lobes. When performing computer simulation, there has been calculated. The directivity pattern of the computer simulated virtual transducer, which was curved along the long transducer axis also was calculated (Fig.11).



a

b

Fig. 9. **Surface holographic interferogram of a bimorph radiator which vibration frequency is 17.16 kHz (a) and normalized three-dimensional distribution of vibrations (b)**

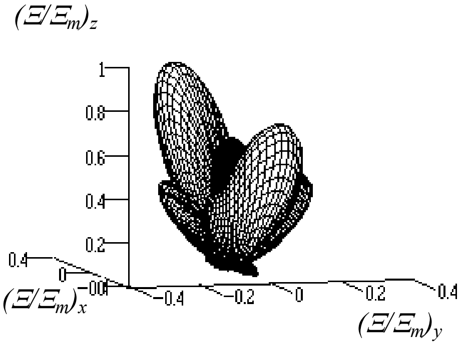


Fig. 10. **Calculated directivity pattern of an ultrasonic radiator, surface vibrations of which are shown in Fig.1a (*f*=30kHz)**

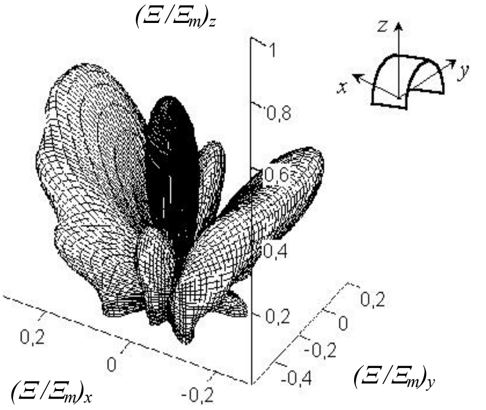


Fig. 11. **Virtually curved radiator (Fig.1a) directivity pattern (*f*=30kHz)**

Comparing with the planar transducer, (10), it may be seen not only the changes of the directivity pattern, but also a significant increase of side lobes. In our work [13] there have been simulated also other cases, such as when the transducer virtually is curved along the symmetry axis or when is deformed along the short symmetry axis.

## Conclusions

When visualizing the acoustic field and measuring vibrations of ultrasonic transducers, having used optical holography methods, it becomes possible to obtain qualitatively new and informative results. In the work carried out by us, there have been investigated some possibilities to use various modifications of the holography method, which allow to investigate both continuous and pulsed acoustic fields, and even separate ultrasonic pulses; to observe on the monitor screen dynamics of acoustic fields; to calculate acoustic fields according to the measured vibrations distributions, and three-dimensional directivity patterns of radiators. The computer-aided processing of the obtained results allows not only present them visually, but also perform simulations of virtual acoustic systems (transducers) fields, choosing various vibration distributions or configurations of radiating surfaces.

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S. Sajauskas

**Ultragarso tyrimai optinės holografijos metodais**

Reziumė

Aprašytas optinės holografijos metodų taikymas ultragarso virpesiams ir laukams tirti. Paprasčiausias ir lengviausiai pritaikomas yra klasikinis dviejų ekspozicijų holografinis interferometrinis metodas, kuriuo galima vizualizuoti virpamųjų sistemų virpesių pasiskirstymą. Pagal užregistruotą pjezoelektrinio keitiklio paviršiaus virpesių pasiskirstymą kompiuteriu galima apskaičiuoti jo kryptingumo charakteristiką, atlikti akustinio lauko modeliavimą. Kintančių ultragarso virpesių paviršiniam pasiskirstymui dinamiškai registruoti patogus dėmėtųjų struktūrų metodas, kuriuo sėkmingai tyrinėtos bimorfinių pjezoelektrinių keitiklių modos. Impulsinės holografijos metodais užregistruotas pavienių ultragarso impulsų tūrinis vaizdas erdvėje. Aukštojo dažnio (MHz diapazone) ultragarso laukams tirti ir rekonstruoti itin naudingas skysčio paviršiaus holografavimo impulsiniu lazeriu metodas. Šiuo metodu galima apskaičiuoti ultragarso lauko energines charakteristikas – akustinį radiacinį slėgį, ultragarso intensyvumą, pjezoelektrinio keitiklio kryptingumo charakteristiką. Aprašyti metodai iliustruojami gausiomis eksperimentinėmis ultragarso hologramomis.

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