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AN ACOUSTIC MICROPROBE

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In the paper the structure of an acoustic microprobe has been presented of which the resolution does not depend on the receiving transducer dimensions. With this microprobe the acoustic pressure amplitude can be measured with the resolution below the wave length in liquid media and at the surface of solids, in the frequency range from 30 to 40 MHz. The method of finding the resolving power of the microprobe by measuring the response function for a point source has been described.

Resolution of the microprobe has been estimated as better than 25 μm what is about 1/2 of the wave length in water and 1/7 of the longitudinal wave length in such materials as aluminium or glass.

The directional response pattern which is necessary for taking measurements at the non-planar surfaces of solids, has been found.

The possibility of applying the microprobe to measuring the pressure amplitude distribution at the surface of lenses used in acoustic microscopy has been demonstrated.

W pracy przedstawiona została budowa sondy akustycznej, której rozdzielczość nie zależy od rozmiarów przetwornika odbiorczego, umożliwiającej wykonywanie pomiarów amplitudy ciśnienia akustycznego z rozdzielczością poniżej długości fali w ośrodkach ciekłych i na powierzchni ciał stałych w granicach częstotliwości 30 do 40 MHz. Opisana została metoda znajdowania rozdzielczości mikrosondy poprzez znalezienie funkcji odpowiedzi sondy na źródło punktowe.

Rozdzielczość mikrosondy oszacowana została na lepszą od 25 μm co stanowi ok. 1/2 długości fali w wodzie i ok. 1/7 długości fali podłużnej w takich materiałach jak aluminium, szkło.

Znaleziona została charakterystyka kierunkowa sondy niezbędna do uwzględniania przy prowadzeniu pomiarów na niepłaskich powierzchniach ciał stałych.

Pokazana została możliwość zastosowania mikrosondy do określania rozkładu amplitudy ciśnienia na powierzchniach soczewek używanych w mikroskopii akustycznej.

1. Introduction

Measurements of pressure distribution of the ultrasound field, for the field shape to be exactly reconstructed, should be carried out with the resolution of at least $\lambda/2$. In the case of the measurements in liquids, when conventional methods are applied (e.g. hydrophones), this becomes practically impossible for the frequencies over 10 MHz. For the measurements of pressure distribution (vibration amplitudes) at the surfaces of solids the holographic method [1] seems ideal. It needs, however, a large power ultrasound field.

There exists a possibility of constructing a very sensitive acoustic probe of which the resolving power would not be determined by the dimensions of the piezoelectric receiving transducer.

In 1980 W. DÜRR, D. A. SINCLAIR and E. A. ASH proposed a method for measuring the acoustic pressure in a liquid and obtained the resolution of $\lambda/4$ for the frequency 4.5 MHz. The similar concept of measurement has been applied in the spike-type acoustic microprobe constructed by me (Fig. 1). Such microprobe would make it possible to measure the acoustic pressure distribution with the resolution of $\lambda/2$ in fluid media and at the surface of solids in the frequency range from 30 to 40 MHz (This corresponds to the wave lengths of 40–50 μm in water and to the longitudinal wave length equal to about 170 μm in such materials as glass and aluminium).

2. Structure of the spike-type acoustic probe

The scheme of the probe is shown in the Fig. 1. It consists of an aluminium cone-shaped spike, with the lithium iodate transducer, operating at resonance frequency of 36 MHz, glued to its base. The spike end is spherically shaped, with radius estimated at 40 μm (measured with the microscopy, by comparison).

The vertical angle of the cone equals $\alpha = 40°$. The ultrasound wave falling on the spike parallelly to its symmetry axis is totally reflected from the side (the angle of total internal reflection of the longitudinal wave on the boundary $H_2$0-Al is 13.5°). Only the spike end transmits the acoustic signal to the surface of the transducer.

From geometrical estimations it follows that only the region with perimeter of about 18 μm is active. As it will occur further this magnitude is close to the microprobe resolution.

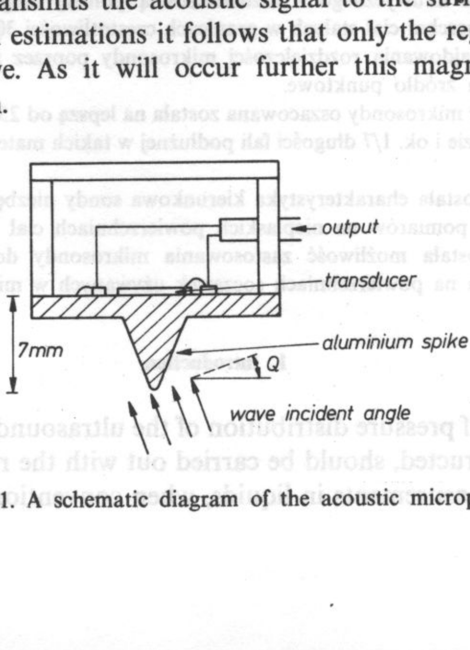

FIG. 1. A schematic diagram of the acoustic microprobe

The spherical shape of the spike end limits its active region on one hand, and allows for better measurement accuracy for non-axially falling waves on the other. These features are indispensable for the measurements of pressure distribution at non-planar surfaces of solids.

3. Measurements of the resolving power of the microprobe

To determine the resolving power of the microprobe the following method has been applied. As it is most generally known the image of an object (u) can be expressed as a convolution of an object function (u_p) and a response function for a point source (image of a point) (h)

$$u(x, y) = u_p(x, y) \otimes h(x, y). \tag{1}$$

If the function $h(x, y)$ could be found then it would be possible to calculate the resolving power of the system from this function.

As the imaged object the pressure distribution in the focal plane of a lens used in acoustic microscopy has been used. This kind of distribution is described by the function type $J_1(x)/x$ [3].

In the calculations I have assumed that the object function is equal to the function describing the theoretical distribution. Actually, this function differs from its theoretical description what implies that the value of resolution, found in this way, can only be smaller than the real resolution.

The theoretical pressure distribution in the focal plane has been approximated with the Gauss function

$$u_p = e^{-(x^2+y^2)/b^2}. \tag{2}$$

This results in considerable simplifications in calculations and have negligible influence on the obtained resolving power of the probe.

The value of b in (2) has been chosen so that the Gauss function would assume the value $1/e \simeq 0.368$ for the same value of the coordinate $(x^2+y^2)^{1/2}$ for which the function which describes the theoretical pressure distribution in the focal plane is also equal to $1/e$. The b value found in this way is

$$b = 0.82 \frac{\lambda f}{d},$$

where f – focal length, d – lens diameter and λ – wave length in water, equal to 38 µm for the frequency 40 MHz.

Analogically, the measured pressure distribution is approximated with the Gauss function

$$u = e^{-(x^2+y^2)/a^2}, \tag{3}$$

where the value of a shoud be found from measurements.

To find the function $h(x, y)$, the functions (2) and (3) were substituted to (1) and then both sides of (1) were subjected to Fourier transform. Taking advantage of the fact that the Fourier transform of the convolution of two functions is equal to the product of the Fourier transforms of these functions and of the fact that the Fourier transform of the Gauss function is also the Gauss function (3), the Fourier transform of the function $h(x, y)$ can be found in a simple way and the function itself can be calculated with the inverse transform

$$h(x, y) = \frac{a^2}{b^2} \frac{1}{a^2 - b^2} e^{-(x^2+y^2)(a^2-b^2)}. \tag{4}$$

With the use of the Rayleigh criterion of resolution, from the impulse response function $h(x, y)$ the resolving power of the probe δ can be found. This resolving power should be equal to the diameter of a circle on which the function h assumes the value equal to 0.81 of the value of this function in the point ($x = 0$, $y = 0$). The resolution found in this way equals the resolution denoted as the value of coordinate $(x^2 + y^2)^{1/2}$ for which the function h would assume the value zero for the first time, if the calculations for the distribution of type $J_1(x)/x$ were used instead of the Gauss function.

$$\delta = 0.92\,(a^2 - b^2)^{1/2}. \tag{5}$$

To find the numerical values of the resolving power, the pressure distribution in the lens focus has been found with the use of the microprobe. In the measurement the system of an acoustic microscope working at the frequency of 40 MHz and at the impulse length 0.5 μs [4] was used. The investigated object (lens) has been connected to the emitting system. The signals received by the microprobe were transmitted to the receiving system of the microscope. Between the lens and the probe there was water. After finding the lens focus the microprobe has been shifted in the focal plane with the mechanical shifting system of the microscope, and the received signal has been recorded with the XY plotter.

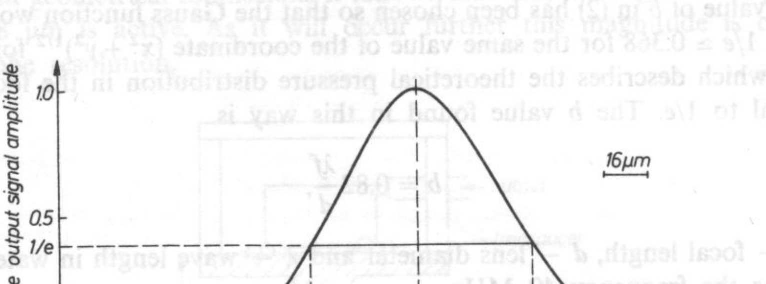

FIG. 2. Distribution of the pressure amplitude in the focal plane of an acoustic microscope lens, measured with the microprobe. Lens dimensions: radius of curvature 3.1 mm, half-angle $\alpha/2 = 50°$. The lens radiates into water with the frequency 40 MHz

The value of a found from Fig. 2 has been substituted to Eq. (5), what resulted in finding the resolving power of the microprobe to be equal about 25 μm.

In the measurements at the surfaces of solids the liquid is applied to wet the surface (e.g. oil). The measurements are carried out at the moment when the probe touches the surface or when it is just above the surface (about 5 μm). In both cases due to the application of a liquid coupling medium, the resolution of the microprobe should be comparable with the one found for the measurements in liquid.

4. The directional response pattern of the microprobe

The measurements of the relation of the signal received from the microprobe to the angle of incidence of the wave on the spike have been carried out. Measurements were always made in the same point of the surface relatively to the transducer which emitted the wave. The results are shown in Fig. 3, together with the theoretically

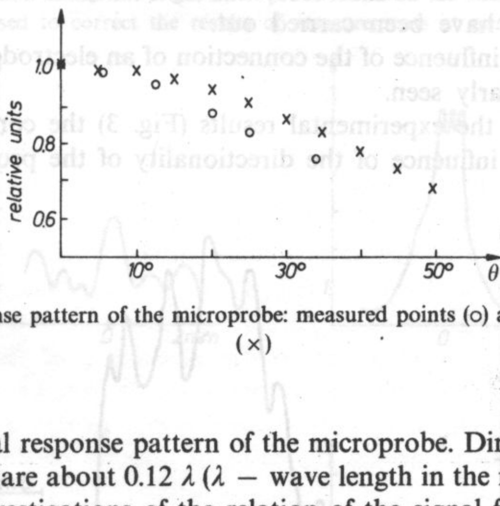

FIG. 3. Directional response pattern of the microprobe: measured points (o) and calculated from Eq. (6) (×)

calculated directional response pattern of the microprobe. Dimensions of the active surface of the probe are about 0.12 λ (λ – wave length in the material of the probe). Therefore, in the investigations of the relation of the signal from the probe to the incidence angle of the measured wave, the results obtained in the paper [5] can be applied. These results concerned the directionality of the longitudinal wave source, with dimensions not greater than the wave length radiating into an elastic semispace. They enable to describe the directional response pattern of the microprobe by the following formula

$$b(\theta) = \frac{v^2 \cos\theta\,(1-2\,v^2 \sin^2\theta)}{(1-2\,v^2 \sin^2\theta)+4v^2 \sin^2\theta \cos\theta\,(1-v^2 \sin^2\theta)^{1/2}}, \tag{6}$$

where $v^2 = (c_T/c_L)^2$, and c_T, c_L are the velocities of the transverse and longitudinal waves, respectively.

The calculated directional characteristic is presented in Fig. 3. The similar, cosinusoidal relation of both curves to the angle supports the statement that the active spike of the probe can be considered as a nearly point-type source which radiates into an elastic semispace.

For growing angles θ the experimental curve departs more and more from the directional response pattern of a source. It seems that this is caused by the fact that the values resulting from the directional characteristic for the given angle θ are greater than the pressure in the transducer plane, averaged by the transducer. The spike end radiates into the cone-shaped region rather than into a semispace, what also influences the above mentioned discrepancies.

5. Measuring capability of the microprobe

When defining the resolving power of the probe its measuring performance in fluids was also presented. The below described examples prove the possibility of pressure amplitude measurements at flat and spherical surfaces of solids.

The measurements at the surface of a glass cylinder with an ultrasound transducer glued on have been carried out.

In the Fig. 4 the influence of the connection of an electrode on the operation of the transducer is clearly seen.

With the use of the experimental results (Fig. 3) the correction factor which compensates for the influence of the directionality of the probe (Fig. 5) has been

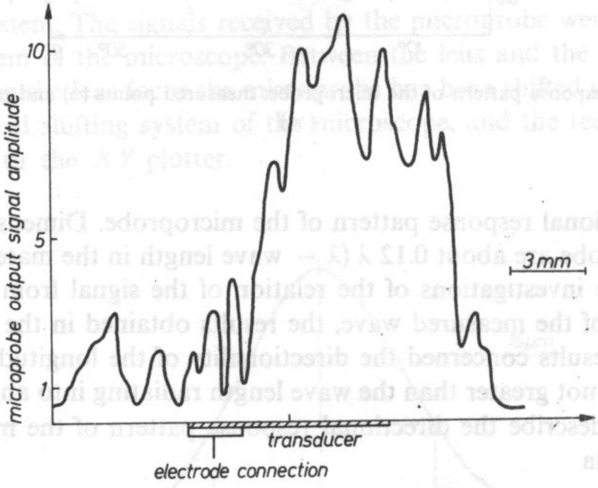

FIG. 4. Pressure amplitude distribution measured with the microprobe at a flat surface of a glass plate of thickness 20 mm. On the other side of the plate a piezoelectric transducer have been glued on. In the figure the position of the transducer and the point of connection of the cable to the transducer is marked. In the amplitude distribution the influence of the connection can be seen. The measurement was carried out at frequency 36 MHz

found. In the correction factor the influence of transverse waves emerging in the spike has not been taken into account because generation of such waves hadn't been noticed in the measurements. The surface waves arising at the spike surface have been damped by applying a wax layer on the spike. The measurement of pressure amplitude distribution at the surface of spherical acoustic lenses used in acoustic microscopy have also been carried out. It has been found that optimal signals were obtained when the lens cap was filled with machine oil. Two lenses with different cap position in the transducer field have been tested. The first, with diameter of 4.5 mm,

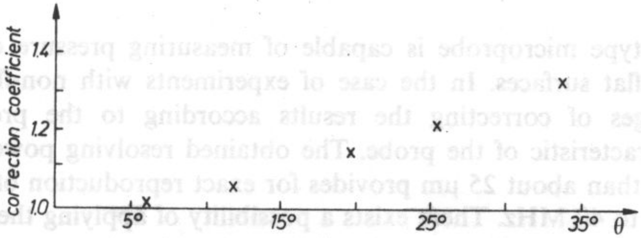

FIG. 5. Plot of the correction coefficient of the microprobe found on the basis of the experimental curve from Fig. 3, used to correct the results of measurements at non-planar surfaces

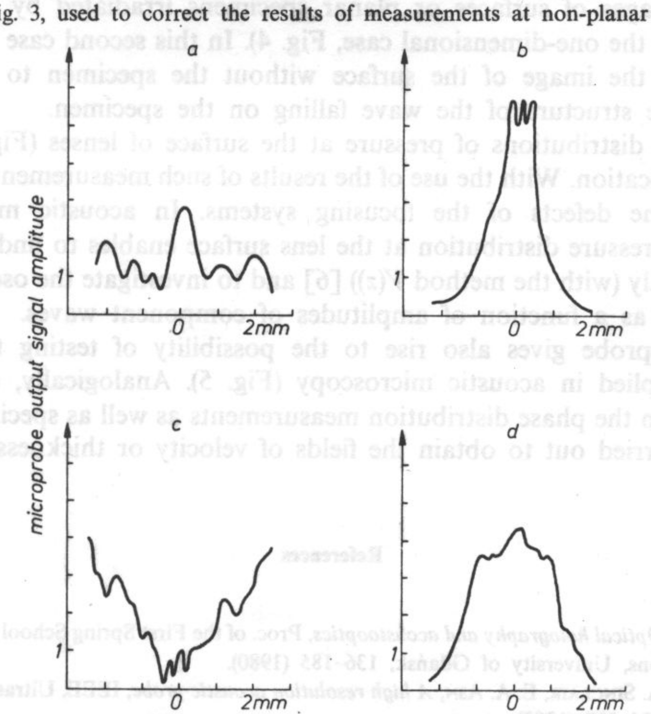

FIG. 6. Distributions of pressure amplitudes at the surface of an acoustic microscope lens of curvature radius 3.1 mm, measured for diverse lens positions in the transducer field: a) z – distance lens–transducer $= 0.42\ d^2/\lambda$, where d – transducer radius, λ – wave length in the medium between the transducer and the lens; b) $z = 1.21\ d^2/\lambda$; c) $z = 0.47\ d^2/\lambda$; d) $z = 1.38\ d^2/\lambda$. Correction according to the plot from Fig. 5 has been applied

was placed in the region between the near and far field ($z \simeq d^2/\lambda$); the second with diameter of 6 mm was in the middle of the near field ($z = 1/2\, d^2/\lambda$). By using the capabilities of the electronical system of the microscope to change the operating frequency within the range of 30–40 MHz it was possible to change the pressure distribution at the lens surface [4]. The results obtained with the correction factor taken into account are shown in Fig. 6.

6. Conclusions

The spike-type microprobe is capable of measuring pressure distributions in liquids and at flat surfaces. In the case of experiments with non-flat surfaces the necessity emerges of correcting the results according to the previously found directional characteristic of the probe. The obtained resolving power of the probe which is better than about 25 μm provides for exact reproduction of wave pressure distribution up to 40 MHz. There exists a possibility of applying the microprobe in place of the receiving lens in the transmission acoustic microscope in forming the microscopic images of surfaces or planar specimens irradiated by a plane wave (analogically to the one-dimensional case, Fig. 4). In this second case it is necessary first to obtain the image of the surface without the specimen to eliminate the influence of the structure of the wave falling on the specimen.

Measuring distributions of pressure at the surface of lenses (Fig. 6) is a very important application. With the use of the results of such measurements it is possible to eliminate the defects of the focusing systems. In acoustic microscopy the knowledge of pressure distribution at the lens surface enables to find the reflection coefficient exactly (with the method $V(z)$) [6] and to investigate the oscillation of the $V(z)$ curve [4] as a function of amplitudes of component waves.

The microprobe gives also rise to the possibility of testing the quality of transducers applied in acoustic microscopy (Fig. 5). Analogically, using a phase detection system the phase distribution measurements as well as specimen visualization can be carried out to obtain the fields of velocity or thickness distributions.

References

[1] A. Śliwiński, *Optical holography and acoustooptics*, Proc. of the First Spring School on Acoustooptics and Applications, University of Gdańsk, 136–185 (1980).

[2] W. Dürr, D. A. Sinclair, E. A. Asn, *A high resolution acoustic probe*, IEEE, Ultrasonics Symposium Proceedings, 594–597 (1980).

[3] J. W. Goodman, *Introduction to Fourier optics*, Mc Graw Hill, New York 1968.

[4] J. Litniewski, *An acoustic microscope in measurements of mechanical properties of surface layers*, Archives of Acoustics, 11, 3, 299–312 (1986).

[5] L. Filipczyński, *Measurements of longitudinal and transverse waves radiated by a compressional source into elastic semispace*, Proc. of Vibration Problems, 5, 2, 89–93 (1964).
[6] K. Liang, G. S. Kino, B. T. Khuri-Yakub, *Material characterization by the inversion of V(z)*, IEEE Trans. on Sonics and Ultrasonics, vol. SU-32, 2, 213–224 (1985).

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