IMPROVEMENTS OF THE RESOLUTION OF ACOUSTIC HOLOGRAPHY BY USING PHASE RECONSTRUCTION

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1. Introduction

Ultrasonic testing is known as a sensitive method for the detection and localisation of reflectors or scatterers like flaws or in solid materials like underwater objects in fluids. For the further description of the reflector-geometry, -size, -orientation and site several imaging methods were proposed like focusing-, phased array- or synthetic-aperture-focus-technique. However, it is not possible to achieve a higher accuracy, because it is limited by the lateral and axial resolution. So the axial resolution in its best is of about one wavelength, because the time of flight is used as data for the image reconstruction.

On the other hand it can be shown, that, using a numerical acoustic-holographic reconstruction formalism considering the phase-angle, it is possible to achieve an improved axial resolution. In this way it will be possible not only to produce topographical contourmaps of a reflector with much higher axial resolution but also to evaluate the motion or the deformation of a reflector f.e. under thermal or mechanical load with a resolution of less than a hundredth of a wavelength /1/.

2. Principles

In modern acoustical-holography an object is scanned within a defined aperture in a liquid or in a surface of a solid, fig. 1

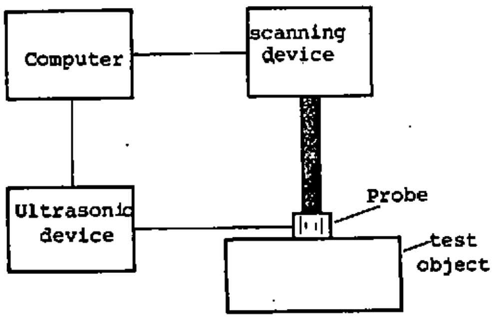

Fig. 1:
Scheme of experimental setup

In general the probe is used in parallel as a transmitter and as a receiver of burst signals. The received signals are multiplicated with a complex reference signal to evaluate both the amplitude and relative phase in every point within the hologram-aperture. An example of hologram data, which are measured in this way are shown in its realpart $A \cdot \cos\varphi$ and its imaginary part $A \cdot \sin\varphi$ in fig. 2.

IMPROVEMENTS OF THE RESOLUTION OF ACOUSTIC HOLOGRAPHY BY USING PHASE RECONSTRUCTION

reflector: disk 5 mm
testmaterial: steel
z = 70 mm
probe: K2K (D=6mm)

N = 128 x 128
f = 2.8 MHz
c = 5,92 mm/µs
AL_H = 50 mm c 50 mm

Fig. 2: A measured complex hologram

In this case the reflector is a flatbottom-hole in a steelblock. The depth of the reflector is z = 70 mm, its diameter is 5 mm, the hologram-aperture is AL_H = 50 mm x 50 mm and the number of the sample points is N = 128x 128. The hologram-data are handed over to a computer which then will perform the image reconstruction. An exact reconstruction formalism is the Kirchhoff diffraction integral:

$$I(x_2,y_2) = \left| \iint_{xy} U(x_1,y_1) \cdot \frac{e^{ikr}}{i\lambda r}\, dx\, dy \right|^2 \qquad (1)$$

Where $U(x_1,y_1)$ represents the hologram-data, i.e. the diffraction spectrum of the reflector in the hologram plane, k is the wavenumber, λ the wavelength and r the radius from a point in the hologramplane to a point in the image-plane. $I(x_2,y_2)$ represents the imagefunction, i.e. the reconstructed sound-field-distribution in the plane of the reflector. A disadvantage of this algorithm is the expense of computing time. It can be reduced drastically by using the Fresnel-aproximation and calculating the convolution product where the Fast Fourier Transform algorithm is included:

$$I(x_2,y_2) = \left| F[U(x_1,y_1) \cdot \exp(ik(x_1^2+y_1^2)/\lambda z)] \right|^2 \qquad (2)$$

Here F represents the Fouriertransform.
In this way the sound-distribution is calculated in the reflector plane with a lateral resolution of one wavelength. However, an information of the reflectorgeometry is not available by this algorithm.
Therefore a modificated algorithm is presented, which allows an imaging of the reflector-geometry in lateral as well as in axial direction at the same time, without requiring more information to be measured, as for instance the time of flight.

In contrast to equ. (2) the real- and imaginary parts U_R and U_I of the hologram are processed separately:

IMPROVEMENTS OF THE RESOLUTION OF ACOUSTIC HOLOGRAPHY BY USING PHASE RECONSTRUCTION

$$I_R(x_2,y_2) = / F\left[U_R(x_1,y_1)\cdot \exp\left(ik\left(x_1^2+y_1^2\right)/\lambda z\right)\right]/^2 \qquad (3)$$

$$I_I(x_2,y_2) = / F\left[U_I(x_1,y_1)\cdot \exp\left(ik\left(x_1^2+y_1^2\right)/\lambda z\right)\right]/^2$$

where I_R and I_I represent the complex soundfield distribution:

$$I_R(x_2,y_2) = I(x_2,y_2)\cdot \cos^2\varphi(x_2,y_2)$$

$$I_I(x_2,y_2) = I(x_2,y_2)\cdot \sin^2\varphi(x_2,y_2) \qquad (4)$$

$\varphi(x_2,y_2)$ describes the phase angle of every reflector point $\varphi(x_2,y_2)$ thus yielding in a value for the location of every point in the axial direction. A division finally yields the phase angle φ itself:

$$\varphi(x_2,y_2) = \arctan\left(\frac{I_I(x_2,y_2)}{I_R(x_2,y_2)}\right) \qquad (5)$$

with a resolution being very small against the wavelength.

Thus knowing exactly the location of every reflector point, also a reflector deformation, which is small against the wavelength, may be evaluated.

For this purpose two hologramdatasets are taken, measured at different times, one before and the other just after a deformation of the reflector. For both hologram-datasets the phase functions φ_1, (x_2,y_2) and φ_2 (x_2,y_2) are computed and a simple subtraction yields the value of the displacement of every reflector point, fig. 3.

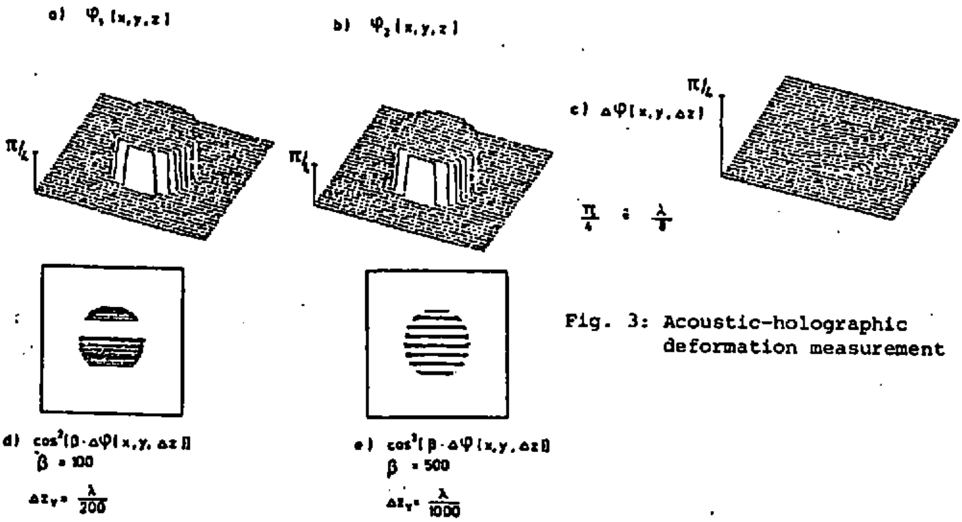

Fig. 3: Acoustic-holographic deformation measurement

IMPROVEMENTS OF THE RESOLUTION OF ACOUSTIC HOLOGRAPHY BY USING PHASE RECONSTRUCTION

In fig. 3a the phase distribution of a disk-like reflector versus the x_2, y_2-plane is shown according to equation (5). Fig. 3b shows the phase-distribution of the same reflector after changing the inclination of the reflector to the sound beam slightly. The difference of the phase angle, i.e. the displacement of the reflector can be observed in fig. 3c. In this case the maximal deflection is of about $7 \cdot 10^{-3} \lambda$, and that means much smaller than the wavelength. Sometimes, if the intensity of an object deformation has to be analyzed, it may be useful to generate a topography-like image, as it is known for example in optics. For this purpose the cosine of the phase angle is computed according to

$$L(x_2, y_2) = \cos^2 [\beta \cdot \Delta\varphi (x_2, y_2)] \quad (6)$$

where L represents an imaging function consisting of lines, which deliver a vivid description of the course of the deformation. Finally by the introduction of a factor ß an adequate density of the lines can be choosen. In fig.3d plots for ß = 100 and in fig. 3e for ß = 500 for the same object are presented.In the latter case the distance between two lines represent a deformation interval of λ/1000. Having a wavelength of 0,5 mm in water using a frequency of 3 MHz the deformation interval here is given to 0,5 µm. In this way the presented 7 lines represent the maximum deformation of 3,5 µm.

By this synthetic example the principal possibility to avail an axial resolution of any part of a wavelength is demonstrated. However, the resolution at the time being is limited by the resulting dynamic range of the experimental setup. But in spite of this still a fraction of a wavelength is availed.

3. Experimental results

For the experimental measurements a testing-device is used as shown in fig. 4.

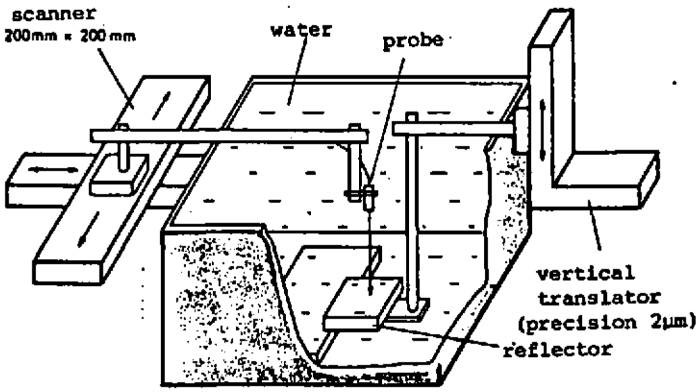

Fig. 4: Testdevice consisting of watertank, scanner probe, testobject

IMPROVEMENTS OF THE RESOLUTION OF ACOUSTIC HOLOGRAPHY BY USING PHASE RECONSTRUCTION

The device consists of a watertank, a probe which is scanned by a two dimensional scanner and the reflector at the bottom of the watertank. The inclination of the reflector can be adjusted by a vertical positioning-device with a precision of 2 µm.

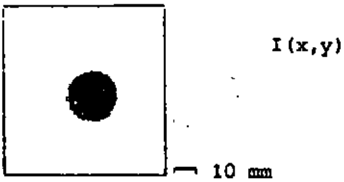

Fig. 5: Conventional Acoustic-holographic image of a disk-reflector in water

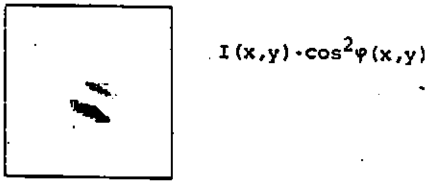

Fig. 6: Topography of the same reflector as in fig. 5

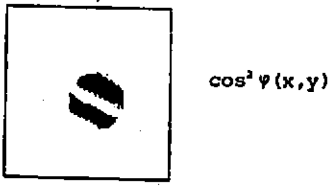

Fig. 7: Improved topography

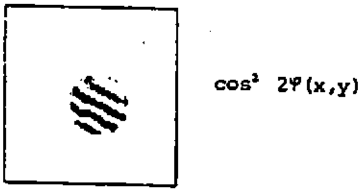

Fig. 8: Topography with a higher density

In the following some results are demonstrated corresponding to the different reconstruction formalisms. In fig. 5 a conventional holographic reconstruction is shown. The reflection is produced by a disk-like steelplate with a diameter of 20 mm in the watertank. The depth is 150 mm. The object is imaged with a lateral resolution of one wavelength, here 1 mm.
An information of the reflectorprofile is not available. Processing of the realpart of the hologram-data according to equ. (4) leads to an image as shown in fig. 6. This topography or contourmap consists of two lines which give an information about the profile of the reflector. In this case the flat plate is slightly inclinated. A further improvement is possible by computing the non-intensity-modulated phase distribution according to equ. (5) and (6), fig. 7.

Here the contour interval is given by $z_H = 0.44$ mm. A higher axial resolution may be achieved by introducing a higher factor ß according to equ.(6), which leads to a higher density of the contour lines, fig. 8. The contour interval is about 0.22 mm, a quarter of the wavelength. From this phase-distribution also the phase-angle can be plotted directly against the x_2,y_2-plane, see fig. 9 for a one dimensional measurement. The inclination is described by $\Delta h = 0.2$mm, and the measuring deviation is of about 7 µm.

According to this phase-reconstruction formalisms it is finally also possible to evaluate an object deformation with nearly the same high resolution, too. An example is given in fig. 10 for a one dimensional measurement. The reflec-

IMPROVEMENTS OF THE RESOLUTION OF ACOUSTIC HOLOGRAPHY BY USING PHASE RECONSTRUCTION

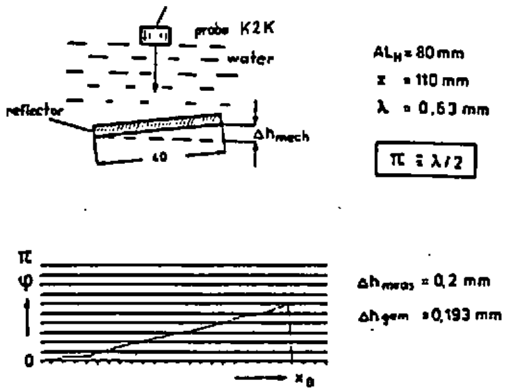

Fig. 9: One dimensional phase-recontruction

torplate was vertically shifted on one side of about 0.1 mm. The measuring accuracy after the reconstruction of the phase distribution and the phasedifference is 2 μm. The accuracy is limited by the dynmic range of the different components of the equipment. The available range of only 40 dB at the time being permits a resolution of λ/100 in case of computing the phase angle and λ/50 when computing the phasedifference.

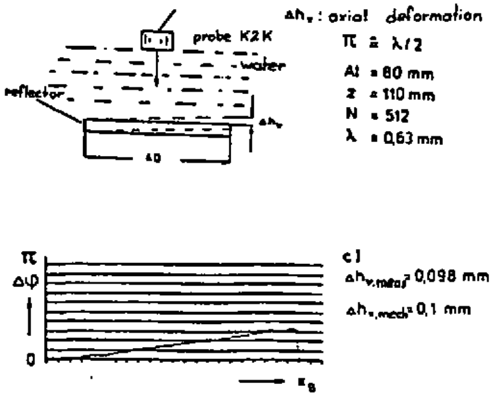

Fig. 10: One dimensional deformation measurement

4. Summary

A new acoustic-holography phase-reconstruction formalism is presented. The algorithms lead to an image of the object within an axial resolution much smaller than the wavelength. Experimental measurements correspond to the theoretical model, being limited primarily by the dynamic range of the experimental setup.

In contrast to the conventional acoustic imaging techniques, the proposed phase-holography has two considerable advantages: The first is given by the high resolution and the second advantages is given by the circumstance that in connection with holography the amount of data to be measured is smaller too, because in every point of the aperture only two values are required - the amplitude and the phase - while other imaging techniques require for the time of flight evaluation a dataset consisting of the full timesignals. Therefore it is possible to implement the proposed holographic algorithms on a relative small and transportable computer and to perform an image reconstruction in an economical time, for example in 1 minute for a hologram of 128x128 points.

References

Crostack, H.-A.,: Verfahren und Vorrichtung zum Erfassen von Fehlern im Inneren von Körpern, insbesondere Bauteilen, mit Hilfe der akustischen Holographie; Deutsches Patentamt, Offenlegungsschrift DE 3217530A1, Mai 1982