TV-HOLOGRAPHY USED TO STUDY THE MUTUAL ACOUSTIC COUPLING BETWEEN NEIGHBOURING ELEMENTS IN A PASSIVE UNDERWATER ACOUSTIC ARRAY.

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1. INTRODUCTION

In an underwater acoustic array, the piezoelectric transducer elements will always interact. There will be a mutual acoustic coupling[1,2] between the elements through the acoustic medium, and through a possible acoustic window.

The mutual acoustic coupling is difficult to calculate and it is therefore also hard to predict the behaviour of the array. The coupling has, however, been calculated for special cases[3-13], most often for active transducers with relative simple shapes and few elements. A rigid and infinite baffle is also often assumed.

In this paper we will use experimental methods to study the mutual acoustic coupling of a passive four-element array at different frequencies. The coupling between pairs of elements will be computed, based on TV-holographic measurements of the surface displacement.

TV-holography, or Electronic Speckle Pattern Interferometry (ESPI), is a full field interferometric measuring technique used to observe and detect small mechanical vibrations[15-17] in "real time" on a video monitor. The monitor image of a test object will be covered by a fringe pattern providing information about the vibration. When sinusoidal vibrations are studied in standard operation mode (time average recording), the fringe patterns are directly dependent on the vibration amplitude. By introducing digital image processing and certain phase-shift techniques, full field numerical phase and amplitude maps can be computed for objects vibrating sinusoidally in the subfringe range. TV-holography has, for example, been used to measure vibrations of objects submerged in water[18-20] with a resolution of less than $\lambda_l/500$.

The TV-holography results will be compared with traditional measurements in a test tank, where the voltage of every single element was measured, and the phase difference between pairs of elements calculated.

2. THEORY

2.1 Acoustics

The acoustic coupling is in the literature expressed as an impedance, <u>mutual acoustic impedance</u> or <u>mutual radiation impedance</u>[4,6]. In order to predict the performance of an array, this mutual acoustic impedance must be known. When the elements have a uniform velocity distribution, the mutual acoustic impedance, Z_{ij}, between element i and element element j, is most often defined as the ratio between a power and a velocity distribution:

$$Z_{ij} = \frac{1}{v_i} \int_{s_j} p_i \, ds_j \qquad (1)$$

v_i is the velocity distribution of the i-th element, p_i is the sound pressure produced by the i-th element on the j-th element, and s_j is the area of the j-th element.

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Foldy[14] has used a somewhat different definition:

$$Z_{ij} = \frac{1}{V_i V_j^*} \int_{s_j} p_i(r_j)\, v_j^*(r_j)\, ds_j \qquad (2)$$

where $p_i(r_j)$ is the sound pressure produced by element #i, $v_j(r_j)$ is the velocity distribution of element #j which has an area s_j, and V_i and V_j are reference velocities of the two elements.

If the velocity distribution is uniform, $v_j(r_j)$ is constant and V_j can be taken equal to v_j. Then Eq.(2) will be reduced to Eq.(1). Even if the sound pressure and the velocity distribution are known the integral is often difficult to compute. This is the reason why the mutual acoustic impedance has been computed only for special simple cases.

If the phase of every element in the array were known, the mutual acoustic coupling could be calculated. A plane wave arriving at angle θ_0 from the array normal will travel an increasing incremental distance $d\sin\theta_0$ to each successive element row (d is the inter element distance). If there is no coupling between the elements, the phase shift, Φ, across the array will be $knd\sin\theta_0$ (k is the wave number $(2\pi/\lambda)$ and n is the number of the element row).
If the measured phase difference differ from this function, this deviation is an expression of the mutual acoustic coupling between the elements.

TV-holographic measurements of the array give the amplitude and phase distribution of every element. To find the average phase of every element the displacement vectors in every point of each element were summed. If the amplitude of point n is expressed as $a_n e^{i\varphi}$, the summation gives

$$a_1 e^{i\phi_1} + a_2 e^{i\phi_2} + \ldots + a_n e^{i\phi_n} = a_1\cos\phi_1 + a_2\cos\phi_2 + \ldots + a_n\cos\phi_n + i[a_1\sin\phi_1 + a_2\sin\phi_2 + \ldots + a_n\sin\phi_n] = X + iY \qquad (3)$$

The average amplitude is then $a = \sqrt{X^2 + Y^2}$ and the average phase $\Phi = \mathrm{arctg}(Y/X)$.

2.2 TV-holography

Only a brief description of the measuring technique will be given here. The reader may consult ref. 21 and 22 for a more complete description.

TV-holography is based on the use of a video system to record interferometric images of objects illuminated with coherent laser light. The object image wave is combined with another coherent wave from the laser, the so called reference wave. The resulting combined image interferogram is transformed into a video signal by the video camera. The video signal is then processed electronically and transformed into a video monitor image. This processed image is modulated by interferometric fringes which contain the information about the vibration of the test object. With a normal image repetition rate the video system will be able to display the vibrations of a test object in real time.

Coherent light reflected from optical rough surfaces always creates speckles[23], and since surfaces investigated by TV-holography are normally rough by optical standard, speckles will always be present in the fringe pattern. The speckles can be considered as vibration information carriers, and as such represent the modulation signal of the interferometric fringes. Due to overlap and narrow bandwidth, the electronic processing does not remove the speckles, which after processing have to be considered as noise. Speckle noise may be reduced by certain speckle averaging techniques[24].

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FIGURE 1. A time average recording of an active transducer. The transducer was excited by a continuous sine signal at 62 kHz, in water. The recording is speckle averaged 256 times.

In so called ESPI time averaged recordings, the fringe pattern resulting from sinusoidal vibrations is directly dependent on the vibration amplitude. Figure 1 shows a typical time average recording of an active underwater transducer. The brightest areas represent the nodal regions or areas with very low vibration amplitude. The interpretation of the dark fringes is like reading height contours with a spacing of about $\lambda_l/4$, where λ_l is the wavelength of the laser light. Going outwards from the dark spot in the circular central area to a brighter circular area, then there is a dark circular fringe before a bright nodal region. The center amplitude peak thus corresponds to the second dark fringe. The transducer probably consisted of seven separate elements, where five are clearly outlined. One might also discern the two remaining elements in the upper part of Figure 1.

By using fringe interpretation in TV-holography, it is possible to look at and interpret changes in the resonance patterns on the video monitor when, e.g., vibration frequency and excitation voltage is changed.

In time average recordings, the intensity I(x,y) of the fringe pattern is proportional to the squared Bessel function of the first kind and zero order J_0^2 [25].

For many applications, the measuring technique described so far is too restricted. The lower limit for an absolute measure is given by the first zero of the fringe function at $\lambda_l/5$ (the first dark fringe), and we also lack information of the phase distribution. Both problems are solved with the ESPI phase modulation feature[26] incorporated in our system. The technique essentially compares the vibration of another vibrating element in the interferometer. The other element is a mirror, mounted on a piezoelectric or an electro-optic crystal. By looking at the changes in the fringe pattern, we find the phase distribution across the entire object surface, and the measuring range is extended. With sinusoidal phase modulation (SPM), the amplitude sensitivity for visual detection is lowered to $\lambda_l/100$[27].

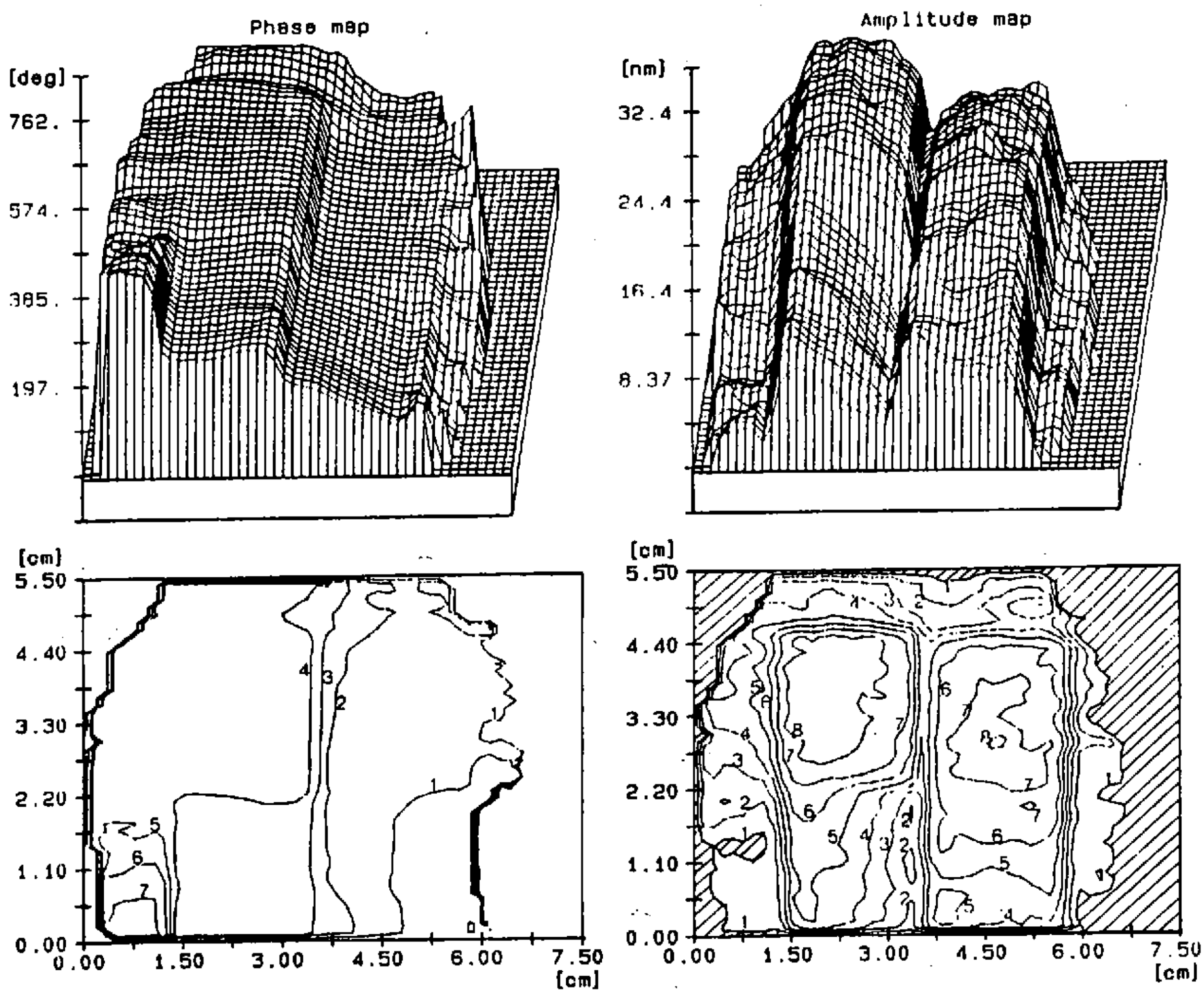

FIGURE 2. Example of the calculated phase and amplitude distribution of a four element passive array, represented by mesh- and contour plots. The phase contour spacing is 45° while the amplitude contour spacing is 2nm. Plane waves fell onto the array at an incidence angle of 50°. The thickness of the acoustic window was 1mm.

As the video signal is easily digitized, an image processing system can be used for further analysis. We see an example from the four-element array transducer in Figure 2, where SPM has been combined with discrete acoustic phase-shifts and digital image processing to provide the phase and amplitude distribution of the array vibrating with low amplitudes. All four elements are clearly outlined in all the plots. The array was recorded in passive mode, which means that an active transducer transmitted acoustic waves towards the passive surface. The vibration amplitudes were well within the subfringe range.

To reduce noise effects of optical (speckle) and electronic noise, the sampling of data is repeated several times, while the object illumination is changed sufficiently between each sample, to alter the speckle statistics. This averaging and smoothing technique has brought the lower limit of amplitude detection down to about $\lambda_l/1000$, in air[28].

3. EXPERIMENTAL SETUP AND MEASURING METHODS

3.1 The four-element array

The four ceramic elements in the array were of PZT4 material and the thickness of the whole element was λ/2. The elements were mounted in a baffle of aluminium, and divinycell was used as backing material. In front of the elements was a 6mm acoustic rubber window. The array had a resonance frequency of about 22kHz.

3.2 Voltage measurements in the test tank

The acoustic array was first investigated in a traditional way in a test tank (SIMRAD Subsea, Horten, Norway). The test tank is 5m x 4m, and is filled with fresh water to a depth of 3.5m. A calibrated sound source with known characteristics, was attached to a mechanical rack which is able to move in 3 dimensions.

The transducer to be measured was attached to another mechanical rack also moveable in 3 dimensions. The distance between the two transducers was about 3m.

The response of the array to short sound pulses was measured before reflected signals reached the surface. The propagation distance between the transmitter and the receiver caused a damping of 9.2 dB.

3.3 TV-holographic measurements

Figure 3 shows a schematic diagram of the setup used to test the transducers with TV-holography. A water tank (dimensions: base area 0.8m x 0.8m, height 0.6m) filled with fresh water was positioned on a vibration isolated table. The transducers were placed in the tank 0.25m under the water surface, to permit observation of the transducer surface through glass windows in the side walls. The tank was made of porous wood which absorbs most of the sound, and echoes from the walls were therefore neglected. The distance between the active and passive transducers was longer than three acoustic wavelengths. The active transducer is supposed to transmit spherical waves. The part of the spherical waves which strikes the transducer surface will at this distance be nearly plane waves.

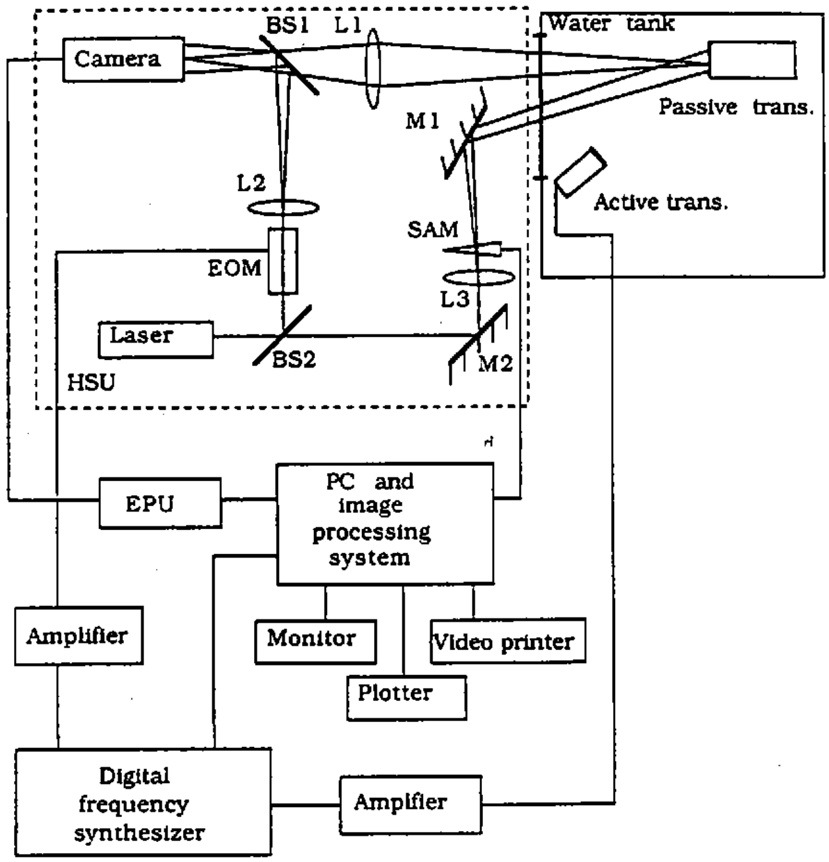

FIGURE 3. The TV-holographic setup.

The basic interferometer was a standard instrument, RETRA 1000 (Conspectum AS), positioned on the same vibration isolated table as a water tank. The detection system was divided in an optical and an electronic part. All optical components were positioned within the Holographic Sensor Unit (HSU), outlined by the dotted rectangle. The laser beam was divided in two branches by beamsplitter BS2, the reference branch and the object branch. The object beam was reflected by mirror M2, and was spread by lens L3 and reflected by mirror M1 to illuminate the object surface. The illumination angle may be altered in small steps, by a PC controlled motor which moved the Speckle Averaging Mechanism (SAM) to produce uncorrelated speckle patterns for efficient speckle averaging. To avoid disturbing reflections from the tank window, the illumination direction (and thus the observation direction) should be slightly tilted from the axis perpendicular to the window plane.

The reference beam will pass through an electro-optic modulator (EOM), where it might be phase modulated. L2 spread the reference beam onto beamsplitter BS1 and the two waves were combined in-line before they interfered at the target of the video camera. The generated video signal was reconstructed in the electronic part, the Electronic Processing Unit (EPU) and the processed signal was displayed directly on a video monitor as a fringe pattern or digitized by the AD-converter on a PC based frame grabber (Data Translation, DT 2861).

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The system has the ability to speckle average 24 video frames between successive steps of the SAM within 9 sec. The motor must not operate during frame acquisition. The averaged images may be displayed as smoothed fringe patterns or used as input data to the computer system for calculation of the phase and amplitude distribution. The computed results may be visualized in different ways, for example as mesh plots.

A two channel frequency generator was essential for correct phase modulation in the data acquisition system. We use a high resolution two tone frequency synthesizer (Hewlett Packard, HP 3326A). The synthesizer was connected to the active transducers and the EOM through amplifiers, which in the EOM's case was a broadband power amplifier (ENI 2100) that supplied the required high voltage up in MHz range.

4. RESULTS

Results are shown in Figure 4a and 4b. Figure 4a represents results from both TV-holographic measurements and voltage measurements at resonance (21.7kHz). In addition the theoretical phase shift without any acoustic coupling is plotted. In Figure 4b the corresponding results are shown for a frequency outside resonance (26.7kHz).

a) b)

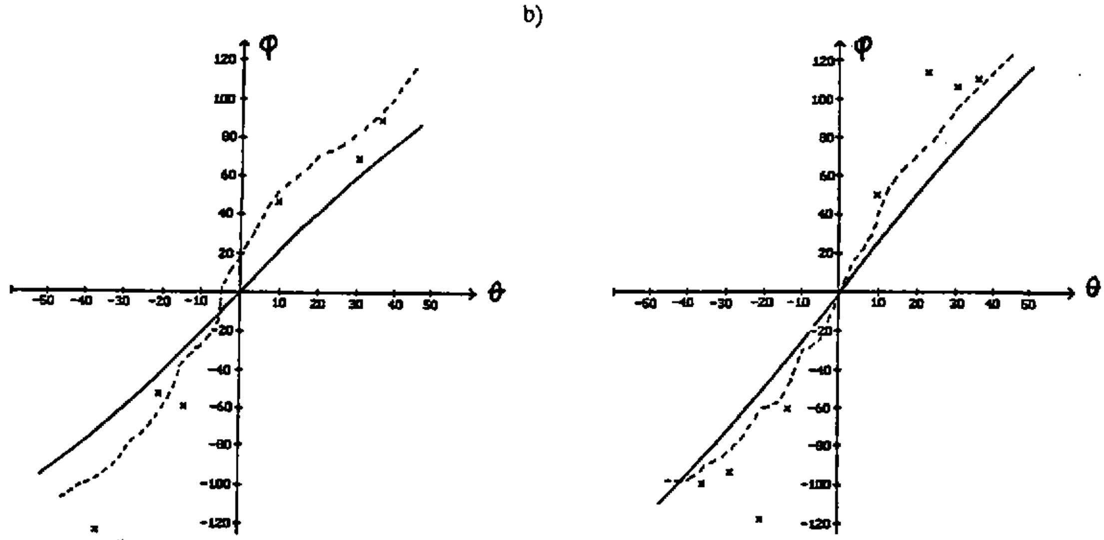

FIGURE 4. Phase shift between elements, Φ, as a function of sound wave incidence angle θ. The solid line is the theoretical result without coupling, the dotted line is an eye fitted curve showing results from voltage measurements for each 5th degree of the incidence angle. The crosses represents results from TV-holographic measurements.
a) f=21.7kHz b)26.7kHz.

5. DISCUSSION

This work has only been a preliminary study of TV-holography as a method to measure mutual acoustic coupling. The deviation between tank and holographic measurements seem to be fairly small for incidence angles lower than 25-30 degrees. Differences can be due due to some reflections from the walls, and also to the fact that the angle measurements has an uncertainty of about ±3°. In future measurements a larger water tank will be used. The distances between the transducer can be increased, and the angle measurements will be more accurate. The walls will be coated with some sound absorbtion material to reduce the reflections. ESPI has two obvious advantage to voltage measurements, the fact that it is possible to observe the transducer surfaces during operation and measurements. Also ESPI gives the phase distribution of every element, while the voltage measurements only gives the average phase difference between two elements.

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