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PARAMETRIC ARRAYS IN SHALLOW WATER.

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Résumé. - On donne un bref compte rendu des principaux résultats obtenus lors de précédents essais de laboratoire à petite échelle, concernant la propagation acoustique dans l'eau en faible profondeur, en comparant les modes de propagation résultant d'une excitation linéaire ou paramétrique. A partir, d'une fréquence porteuse de 4 MHz avec une modulation d'amplitude de 100 % égale à la fréquence différence (400 kHz) on a réalisé l'excitation paramétrique du mode inférieur (le premier) dans un bassin peu profond et sous différentes conditions d'environnement, dans le guide d'onde acoustique constitué par une couche d'eau douce isovitesse de 60 mm d'épaisseur et ses parois. Les modifications des conditions d'environnement comportent :

a) l'application de différents matériaux sur le fond du bassin (béton, tapis de caoutchouc, sable).

b) la mise en place d'obstacles de géométries variées sur le trajet de propagation des modes.

c) l'introduction d'un fond incliné.

Abstract. - A brief account of the most essential results obtained by some earlier small-scale laboratory tests on underwater sound propagation in a shallow-water area is given comparing both linearly and parametrically excited mode propagation. Using a 100 % amplitude-modulated carrier (4 MHz) with a modulation frequency equal to the difference frequency (400 kHz) the parametric excitation of the lowest (first) mode has been performed in a shallow-water basin under the influence of various environmental conditions in the acoustic waveguide formed by the 60 mm deep isovelocity, fresh water layer and its boundaries. The changes is environmental conditions include : (a) the application of various bottom materials, concrete, rubber mats and sand, (b) the placing of obstacles of various geometrics in the propagation path of the modes, (c) the introduction of a sloping bottom.

1. INTRODUCTION. - Long range underwater communication systems naturally have to operate at low frequencies due to the strong increase in signal absorption with frequency generally observed. Another restriction on sound propagation arises from limitations in the water depth which on continental shelves and in shallow-water areas as for instance the North Sea, the Baltic and the Mediterranean frequently is no more than 10 to 100 wave lengths of the underwater sonar signal. In this situation the water column becomes an acoustic waveguide the signal propagation in which is strongly influenced by the bottom and the surface. The transmission of parts of the signal into the bottom, for instance when the bottom structure allows the transmission of strong shear waves, may lead to a great loss of energy during signal propagation in the water column, the scattering from the roughnesses along the waveguide boundaries, for instance from surface waves and from varying topography of the bottom, leads to further losses, and the establishment of thermal and salinity gradients refracts the sound beams. Moreover, most conventional (linear), low-frequency sound sources produce multimode excitation where several modes simultaneously excited interfere with each other.

This very complicated nature of underwater sound propagation may be strongly simplified by the use of parametric acoustic arrays. The super-directivity of the parametric beam and its lack of sidelobes, for instance will make the signal propagation more uniform, more coherent and less subject to multipath propagation and to modal interference. Moreover, the choice of a parametric system instead of a conventional linear one will seem desirable due to its frequency agility and bandwidth and in particular due to the fact that it opens up possibilities of selective excitation of discrete normal modes which allows one to concentrate the propagation of acoustic energy along ray paths corresponding to natural spatial resonances of the waveguide formed by the shallow water /1/, /2/, /3/, /4/.

The principle of decomposition of the shallow water wave propagation into orthogonal modes has been known for a long time /5/. Physically the formation of a mode can be considered the result of an interference between a down-going and an up-
going wave of equal, but opposite inclination with the vertical direction. The angle of inclination increases with the mode number and it decreases with the frequency. Unattenuated propagation of a mode over a distance demands perfect reflection of the two interfering waves at the surface - due to impedance mismatch - and at the bottom - due to total internal reflection of waves incident beyond the critical angle - , which leads to a vertical distribution of pressure associated with the mode represented by a succession of zero and maxima and with a phase inversion of $\pi$ occurring at each zero crossing. The number of zero crossings between the surface and the bottom represents the mode order and the first zero will always be situated at the water surface.

The distribution with depth of the acoustic pressure in each of the normal modes of propagation is a sensitive function of the vertical sound speed profile. Tidal currents, fresh water runoff from adjacent land masses, and diurnal heating and cooling, being characteristic of shallow-water areas of the sea, tend to produce sound speed profiles which vary widely with time and location.

The first mode, i.e. the lowest mode, is the most important for long range sound propagation in shallow water. If more than one mode is present, mode interference can be expected. The mode interference is strongest when only two modes of comparable strength are present.

The experimental investigations of sound propagation in shallow water have during the past mainly been performed as full-scale tests at sea or as model-tank laboratory experiments. Both procedures have advantages and disadvantages. Model-tank experiments make it easier to control the parameters influencing the sound propagation, thus giving more flexibility in the choice of test parameters. Moreover, they are frequently less expensive than full-scale tests, the manual operations during the measurements can easier be performed, the necessary instruments are at hand etc., but model-tank experiments are frequently beset with scaling problems which can lead to serious deviations between small-scale and full-scale results and conclusions based thereon. In spite of this fact model-tank experiments have long been recognized as an important method to obtain valuable information about underwater sound propagation, but it should be emphasized that model-tank results mainly are of a qualitative character.

A.B. Wood /6/ gave an example of outstanding use of model-tank technique in the investigation of shallow-water sound propagation. Through the use of an arbitrarily chosen scaling factor of 1 : 1000, approximately, he studied mode propagation under influence of bottom materials, of surface waves, of temperature stratification and of depth variations due to a sloping bottom. Through this masterpiece of a laboratory experiment he showed how whole series of valuable information in detail illuminating the nature of mode propagation in shallow water could be obtained by some relatively simple model-tank measurements.

Like Wood, also Eby et al /7/ used conventional sound sources for their model studies. Moreover, they included absorption effects together with shear waves in a bottom model consisting of a Hycar rubber slab simulating the stress wave propagation capabilities of a sedimentary bottom. For Hycar they found the same linear absorption dependence on frequency as found later for a broad variety of sediments /8/. One of the essential features of their work was the important conclusion, that a first mode can be generated and received with little or no admixture of second or higher modes by appropriate adjustments of the signal source and the receiver depths. This simple technique will, unfortunately, not work for the generation of the second mode alone. Eby et al also showed how mode conversion may be caused by an abrupt change in the water depth while a random distribution of small roughnesses produced no higher modes. Attempts to excite, to stimulate and to receive single, preselected, individual modes by an appropriate "tailoring" of linear transmitting or receiving arrays have recently been shown great interest by various scientists /9/, /10/, /11/, /12/, /13/. These transducer arrays must however be tailored to a specified combination of water depth, acoustic frequency, sound-speed profile, bottom qualities, and mode number and will therefore suffer from an inherent lack of flexibility.

Only recently successful attempts to excite individual modes using parametric arrays have been done /1/, /2/, /3/, /4/, /14/. The pioneer work in this field has been done by the group around Dr. T.G. Muir in the Applied Research Laboratories at the University of Texas at Austin. Through theoretical and experimental studies they proved it to be possible to excite preselected single modes.
by an appropriate tilting of the array axis an angle \( \phi \) being characteristic for the mode to be excited by the narrow difference-frequency beam. A good agreement between calculated and experimental depth functions for the lowest (first) mode difference-frequency sound pressure level at various source distances was obtained by Dr. Muir's group. Through experiments performed in a shallow-water tank facility and in a shallow-water lagoon allowing long range propagation over approximately constant water depth they showed the superiority of the parametric array over a conventional source when multimode excitation should be avoided and the echo/reverberation ratio should be improved. Very recently the simultaneous excitation of the vertical and horizontal lowest modes were studied in a water-filled channel illuminating mode interaction problems [14/].

2. EXPERIMENTAL EQUIPMENT AND EXPERIMENTAL PROCEDURES. - An air-backed piston source - PZT-26, manufactured by Ferroperm A/S, Vedbaek, Denmark - transmitted a 100 \% amplitude modulated carrier wave, modulation frequency equal to the difference frequency, into a layer of isovelocity fresh water. The natural frequency of the piston source, \( f_0 = 4 \) MHz, formed the carrier frequency and a modulation frequency of 400 kHz was used for most experiments, and the interaction of each sideband, thus formed, with the carrier produces a difference-frequency component \( f_s \) at the modulation frequency. As shown previously [15/1, 16/], the difference-frequency pressure amplitude achieved using 100 \% modulation of a carrier exceeds the value achieved with a two-component primary wave system by 2.5 dB, if the primary signal in each case has the same total power.

The effective diameter of the piston source was 10 mm and the speed of sound in the water was approximately a constant (= 1487 m/s) during all experiments. The data for the acoustic parameters of the array used for the experiments are:

1) Carrier frequency: 4 MHz.
2) Difference frequencies: 400 kHz (used in most series of experiments)
3) Carrier half-power beamwidth: 1°0.08 (angle between half-power point and acoustic axis)
4) Piston source directivity index: 38.5 dB (at 4 MHz)
5) Half-power beamwidth of piston source running linearly at \( f_s = 400 \) kHz: 21°0.6.
6) Primary source level: 202 dB re 1 \( \mu \)Pa at 1 m (4 MHz).
7) Parametric source level: 152.6 dB re 1 \( \mu \)Pa at 1 m (400 kHz).
8) Pulse length: 100 \mu s.
9) Array length: \( L = 1.45 \) m.
10) Rayleigh distance: \( R_n = 0.21 \) m (at 4 MHz).

<table>
<thead>
<tr>
<th>( f_s ) (kHz)</th>
<th>( \theta_h ) (deg.)</th>
<th>( \phi_d ) (deg.)</th>
<th>( D ) (m)</th>
</tr>
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<tr>
<td>200</td>
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<td>3.55</td>
<td>1.94</td>
</tr>
<tr>
<td>400</td>
<td>1.64</td>
<td>1.78</td>
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<tr>
<td>600</td>
<td>1.34</td>
<td>1.18</td>
<td>5.81</td>
</tr>
</tbody>
</table>

Table I. - Half-power beamwidths \( \theta_h \) for various difference-frequencies \( f_s \) of the parametric array. Modal separation angle \( \phi_d \) and cycle distance \( D \) (first mode).

The predominantly spreading loss limited array will have the difference-frequency half-power beamwidths \( \theta_h \) given in Table I. \( \theta_h \) denotes here angle between the half-power points and the array axis. This table moreover gives the modal separation angle \( \phi_d \) and the cycle distance \( D \) (first mode) [14/], [15/], for mode propagation under the experimental conditions, isovelocity fresh water with a constant depth \( H = 60 \) mm. Except for \( f_s = 600 \) kHz the condition of \( \theta_h \leq \phi_d \) is satisfied in order to concentrate the maximum amount of parametric energy into a given mode.

Influence of phase reversals during reflections at the surface and the bottom will only be very weak due to all first reflections taking place far beyond the 3 dB-distance of the primaries for all tilt-angles used in the experiments.

Measurements of the primary and difference-frequency sound pressure level were performed using a mini-hydrophone showing a sensitivity at 400 kHz of 0.4 \( \mu \)V/\( \mu \)bar [16/].

All experiments were performed in a shallow-water basin. This basin, having the dimensions: \( 12 \times 1.6 \times 0.15 \) m, consisted of a wooden frame mounted on a concrete floor an lined with a thick-walled polyethylene foil in order to obtain water tightness.
The acoustic waveguide boundary conditions by the bottom could be changed by the introduction of materials like a rubber slab or a layer of sand to simulate seabed conditions. Moreover, the basin facility was provided with a facility for generation of waves on the water surface.

The piston source was mounted on a car allowing it to be moved along the longitudinal and transversal axis of the basin and to be moved in depth. Furthermore, it could be rotated 360° in the horizontal plane and it could be tilted with an accuracy better than 0.1° using a thread gear. Calibration of the horizontal position of the array axis was performed using a laser beam to be reflected by the piston source surface. The tilt angles used were calibrated using the same procedure.

The receiver, a mini hydrophone produced in the Department of Fluid Mechanics, was mounted on a car being free to move on rails in the longitudinal direction of the basin. In order to achieve a continuous and automatic registration of the sound pressure level variation in depth and in the transversal direction of the basin the hydrophone movements in these directions were controlled by a step-motor governed by a preset-index device.

The electronic instruments used for the beam-forming, the signal processing and the registration on oscilloscopes and on paper tape are shown in Figure 1.

Registrations of depth functions and sound pressure level variation in the transversal basin direction were performed at various piston source distances through 6 series of measurements. These measurement series comprised parametrically generated signals propagated in the following environ-

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Fig. 1. - Block diagram for electronic equipment used by the experiments.
Fig. 2. - Linear and parametric transmission of 400 kHz into a water column of constant height, 60 mm, over a concrete bottom. All distances are measured from the piston sources surface.

ments:
1) Concrete bottom and constant water depth.
2) Rubber mat bottom and constant water depth.
3) Sand bottom and constant water depth.
4) Items of various geometries situated on sand bottom by constant water depth.
5) Sloping sand bottom without and with items on the bottom.
6) Transversal scannings by constant water depth over sand bottom.

3. EXPERIMENTAL RESULTS AND DISCUSSION. - All experiments were performed in fresh water at constant temperature, 22 °C, in order to avoid the influence on the mode propagation arising from a vertical sound speed profile.

During all experiments the piston source was in middepth in order to excite the first (lowest) mode being the most important for long range propagation.

Figure 2 shows a comparison between linearly and parametrically produced depth functions in the mode propagation over a concrete bottom at a constant water depth of 60 mm. The frequency is in both cases 400 kHz. The linearly produced depth functions show the usual effects of multimode interference while the parametrically produced depth functions are smooth, indicating a strong reduction in multimode interference and a strongly prevailing energy propagation in the lowest mode. Some weak influence of the bottom absorption - probably due to propagation of shear waves in the concrete - may be seen on the parametric curves at greater source distances.

Increased absorption by the bottom materials can be observed in Figure 3 when a 3 mm thick, soft rubber mat is covering the concrete bottom. In spite of the tilt angle being kept on 0° the complex wave number of the rubber seems to have a not vanishing influence on the parametric depth functions. This influence is on a par with the one observed by Wood /6/ and Eby et al /7/.

Even if some redistribution of energy in the depth takes place with increasing source distance, most energy is propagated along in the lowest mode. A weak influence of higher modes - probably the 3rd mode - can be seen over the rubber mat at source distances 5 and 6 m.

The influence of a 15 mm thick layer of sand
Fig. 3. - Comparison between parametric depth functions measured over a free concrete bottom and a concrete bottom covered by a 3 mm thick rubber mat.

Fig. 4. - Comparison between parametric depth functions for a free concrete bottom and for a concrete bottom covered by rubber mat and 15 mm thick layer of medium sand.
covering the rubber mat and the concrete bottom on the parametrically generated depth functions for tilt angle 0° in a water column of 60 mm may be seen in Figure 4. The presence of higher modes due to the influence of the sand bottom may clearly be seen in the figure. The speed of sound and the absorption coefficient for the medium sand used was measured to be: 1765 m/s and 22 Np/m (at 400 kHz) /17/.

The influence of the tilt angle on the parametric depth functions over the sand covered bottom is shown in Figure 5 for negative, i.e. downward pointing, tilt angles: -0.5°, -1.0° and -1.5°. A stabilization of energy propagation in the lowest mode, in particular at -1°, seem to take place by the negative tilt angles. By positive tilt angles of the same magnitude as the negative ones, Figure 6 shows destabilization of the lowest mode to occur and a mode interference with propagation distance takes place, presumably between the 3–4 lowest modes. Changes in the environmental conditions in an acoustic waveguide may strong-

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**Fig. 5.** - The influence of negative tilt angles on the parametric depth functions over the sand bottom at constant water depth 60 mm.
ly influence the mode propagation. Obstacles, which due to their position in the shallow water and due to their specific acoustic impedance differing from the one of the environment, may lead to mode interference and to re-distribution of modes. These changes will be reflected in modifications in the course of the depth functions, which in a very convincing way is shown in Figure 7. This figure shows a water-filled iron tube, outer diameter 17 mm, positioned on the sand bottom at various distances from the piston source. The tube axis, forms a right angle with the parametric array axis. The three series of depth functions in Figure 7 show a comparison between the mode conditions without the iron tube, and with the iron tube at positions $R = 2.10 \text{ m}$ and $R = 4.10 \text{ m}$. The disturbing influence on the depth functions arising from the presence of the iron tube seems to be present even in depth functions far "down-stream" from the tube. Also the depth function "up-stream", i.e. at $R = 3.0 \text{ m}$, from the tube on position $R = 4.1 \text{ m}$ seems to be exposed to some reflection influence. The strongest influence of an obstacle on the course of the depth functions should be expected when its position coincides with a null in the depth function of the specific mode considered thus preventing the field
strength of the mode to go down to zero.

A solid block of iron positioned at various distances from the piston source in Figure 8 shows some of the same features in its influence on the depth functions as observed by the iron tube. A strong redistribution of the propagating acoustic modes is the result leading to a persistent change of shape by the depth functions.

Change in environmental conditions for the mode propagation may also arise from a sloping seabed. Figure 9 shows a comparison between depth functions measured above a sloping bottom of sand (slope angle: 1°) without and with obstacles influencing the course of the depth functions. A certain focusing effect seems to be present above the sloping bottom, in spite of the increased absorption to be acting on the modes due to the increasing number of reflections by the bottom material. A considerable mode conversion which is further amplified due to the presence of the obstacles can be seen in Figure 9.

All depth functions previously shown are measured through the acoustic axis of the parametric beam. Measurements of depth functions off-axis
Fig. 8. - Influence of a solid iron block situated on the sand bottom on the depth functions measured at various distances from the piston source.

at various transversal positions at a piston source distance $R = 3.5 \, \text{m}$ are shown in Figure 10. Well-developed transversal symmetry in the distribution of sound pressure level with depth around the peak value in the beam-axis depth function are shown in Figure 10. This symmetry was in general found at all other piston source distances in the shallow-water basin.

4. CONCLUSIONS. - The experimental results presented in this paper seem to support the applicability of the parametric array in a shallow-water area even if obstacles on a sloping bottom changes the environmental conditions in the acoustic wave guide. In spite of the mode conversions observed caused by changed environmental conditions the parametrically excited lowest mode seems to survive over longer distances of propagation carrying most of the acoustic energy along even if a limited
number of higher modes are simultaneously present. The course of the measured depth functions shows that this number of higher modes introduced by modified environments is much lower than the number of modes linearly excited under the same conditions in a shallow-water waveguide.

REFERENCES


Fig. 10. - Off-axis depth functions measured at various transversal positions at a piston source distance $R = 3.5$ m.


