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REFERENCE NO. 69-12

PART I. A CONTINUOUS CONFIGURATION HYDROPHONE
ARRAY FOR BROADBAND CONTINUOUS SEISMIC PROFILING

by

S. T. Knott

PART II. A COMPARISON BETWEEN THE RESPONSES OF
A CONTINUOUS LINE ARRAY AND A DISCRETE LINEAR ARRAY

by

R. T. Nowak

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Woods Hole, Massachusetts

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April 1969

TECHNICAL REPORT

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Earl E. Hays, Chairman
Department of Geology & Geophysics

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PART I

A CONTINUOUS CONFIGURATION HYDROPHONE ARRAY
FOR BROADBAND CONTINUOUS SEISMIC PROFILING

by

S. T. Knott

ABSTRACT

The signal-to-noise ratio of towed receivers employed in seismic reflection profiling is significantly improved by using a hydrophone array whose broadband directional response approaches that of a theoretically continuous sensor. Within a broad pass band all secondary lobes of an array of continuous configuration are less sensitive than the main lobe. This design improves upon the directivity and thus the signal-to-noise ratio realized in broadband work by those linear arrays in common use whose transducers are spaced widely compared to the wavelength and duration of transients of acoustical noise projected along the array from all angles of reception. Sensitivity equal to that of the main lobe is developed by the secondary lobes of these commonly used arrays at various frequencies and angles to the array.

The 30-meter arrays of 200 equally-sensitive transducers described here have a broadband response approaching that of a continuous configuration. In order to obtain uniform sensitivity along the array all transducers are calibrated and chosen to be equal in sensitivity within ± 0.4 dB. Long term stability in sensitivity is attained by the use of small, rugged, cylindrical ceramic transducers. The ratio of seismic signal-to-noise from all sources in a 20 to 1000 Hz passband is about +6dB while deep-ocean profiling with a 90 k joule sparker at 8 kts in a moderate sea state. The average seismic signal received 1 second after the onset of the bottom reflections during a 0.5 second period is compared with the average noise received in the same passband for a similar period just prior to the bottom reflections.

INTRODUCTION

Improved signal-to-noise ratio is the fundamental goal of most new instrumentation applied to the technique of broadband seismic profiling. To this end, in 1968 a broadband receiving system was designed and built in which the summation of the outputs of two new hydrophone arrays were used (Knott and Bunce, 1968). This report describes the design objectives, the principal features, and the general construction of the new arrays.

The use of broadband sound pulses to probe the structure of the Earth beneath the oceans and other water bodies has been a primary objective of continuous seismic profiling (CSP) from the time of its earliest developments (Hersey, 1963) (Knott, Hersey, 1956). By following this frequency dependent approach much has been learned about the shape of the sediment and rock structures beneath the seafloor, and also something of the "response" of the reflectors, eg., their spacing, material, and absorptive and reflective qualities.

The frequency band of interest is broad, from less than 20 Hz to several kHz. The energy spectrum of the noise, derived by field observations and measurements, received in this band by towed hydrophones is somewhat similar in shape to the spectrum of the source (ie., an underwater spark) and also that of the ambient noise of the sea. Each is rich in low frequency energy with progressively-lesser contributions at the higher frequencies. For the most part ambient noise levels are adequately known and on the average establish the minimum signal levels. The downward radiated energy of many of the sources may also be reasonably predicted. Their output in most cases is in the form of a pulse train whose spectrum is modulated by a function related to the spacing in time of the output-pulses of the source and their phase-inverted reflections from the sea surface. Although source levels may be marginal for some CSP research, the real performance limiting factor is the total noise received by towed hydrophone systems. The noise spectra received by different towed hydrophone arrays vary more widely and unpredictably than do ambient noise and source spectra for many reasons, eg: the natural environment (weather, wind, and sea state); the broadband directivity of the receiver; the proximity to noise sources outside the hydrophone system (ship's propulsion and power machinery); the many features of mechanical design of the receiver (how the elements are

supported, the diameter and material of the array skin, the tensile members, and the mechanical and thus acoustical coupling between receiver and tow cable); the type and length of tow cable (either hard, sinewy, and easily vibrated or damped by flotation foam); the tow point (submerged or in the air, its position relative to the ship's wake); the degree of buoyancy and the uniformity of buoyancy of the towed assembly; the speed and depth of tow (flow noise, ship's propulsion noise, and changes in transducer response with ambient pressure).

As CSP has been put to more routine use, greater exploratory coverage has been sought with resultant increases in ships' speeds. Thus the design of the new array has emphasized the reduction of flow noise or the self-generated towing noises of the arrays, the reduction and decoupling of cable-borne noise from the arrays, and an improvement in the broadband directivity of the arrays. Improvements have been made in each of these categories. The following are typical of the first two. The use of smaller diameter arrays 25 mm or less as compared to 60 to 90 mm reduces noise background, presumably flow noise (Windisch and Ewing, 1967; Knott and Bunce, 1968). Deadened tow cables, damped by applying a woven-braid strain member and foamed flotation over conventional electrical cables, reduces cable-generated and-borne noise (Knott and Bunce, 1968). It is often difficult, however, to isolate whether a change in signal-to-noise ratio is due to a reduction in cable-generated and-borne noise or to a reduction of the flow noise of the array. For instance a significant reduction in noise results from simply towing an array, either large or small diameter, outside rather than inside the ship's wake. The change to towing in the less turbulent environment probably influences the generation of and reception of noise from both sources, but exactly how much remains a question. Rather than measure these differences exactly, it has most often been adequate to note that a new technique has improved the profiler records.

In 1965 F. R. Hess, R. T. Nowak, and the author concluded from simple array theory that a linear array approaching a theoretically continuous, uniformly sensitive configuration would produce a directivity pattern more uniquely useful for this work than the openly spaced arrays then in use. If a linear array is equally sensitive along its length and its frequency response is broadband, a continuous configuration assures that all secondary lobes of the directivity pattern to either side of the perpendicular main lobe are less sensitive than the main lobe at any frequency within its designed passband. It has not generally been appreciated in broadband seismic profiling work that an array whose transducers are spaced at dimensions

several times greater than the wavelengths of the higher frequencies projected along the array does have secondary lobes that are equal in sensitivity to the main lobe at various angles and various frequencies within the band of interest. A summary of the differences between these two simple array designs is given by R. T. Nowak in Part II of this report.

The reduction in the reception of ship-generated noise and noise transients is one of the most obvious results of using the continuous configuration. Although earlier arrays such as those described by Hoskins in Caulfield et al., (1965) and Windisch and Ewing (1967) did improve previous techniques, long lengths of towing cable (250 to 500 meters) were required so that the arrays would tow in a quieter environment than that near the ship.

A practical approach to the continuous configuration is a 200-element, 30-meter-long, 25.4 mm diameter, linear array described by Prada (1967). The low-frequency directivity of the array is controlled by its length. The frequencies at which side lobes may become equal in sensitivity to the main lobe is dependent upon the spacing of the transducers, the angle of approach, and the propagation velocity. Similarly the response to transients is dependent upon the duration of the transient, the angle of approach, the propagation velocity, and the number and spacing of transducers. A frequency higher than the useful limit of the array's frequency response is exemplified by the end-fired response to a signal of about 10 kHz where transducer spacing (152 mm) and signal wave-length are about equal.

The performance characteristics of different arrays in profiling application are difficult to compare, but a reasonable evaluation may be obtained as follows. If the broadband output of an array is monitored as the tow cable is paid out while the ship is underway at a given profiling speed, the overall noise level drops at first, roughly inversely proportional to the square of the cable length or the range from the ship to the array. Ship noise may override other tow noises at short range, but when cable length is increased the overall noise tends to drop to a plateau where cable-generated and-borne noise and the array's self-generated noise become dominant. (An array could have such a high level of self-generated noise that it dominates ship noise, and the ship may be unusually quiet; and thus noise would not decrease with greater range). The R/V CHAIN a former Navy salvage tug, diesel-electric driven from which much of this work has been done, produces a relatively high noise background.

Therefore the merits of particular array designs have been based on a consideration both of the length of cable required to reach the noise plateau where tow noises caused by the cable and array are dominant, and a seismic-signal-to-tow-noise ratio taken at that range. As a result of these comparisons it is clear that an array of continuous configuration, because of its improved broadband directivity may be used successfully at relatively close range to the noise producing ship.

Arrays of the continuous configuration 25.4 mm in diameter have required only 25 to 150 meters of cable to reach the self-noise plateau. At this distance from the ship and at towing speed of 6 kts the signal-to-noise ratio is sufficiently favorable to obtain clean-cut broadband (15 to 1000 Hz) records of reflections 2.5 to 3 seconds deep (two-way travel-time) below the deep-sea floor. Records made at the same time with a 76.2 mm diameter array of 10 elements spaced 1.8 meters apart and towed 250 to 500 meters astern show the deep reflectors if the signals are filtered in a narrow band (30 to 70 Hz), but if ship's speed is increased to 7 knots the signal-to-noise ratio in this narrow band is poor. The signal-to-noise ratio of the continuous-configuration array is favorable at 8 to 10 knots or more.

When Prada (1967) made his array, the transducers commercially available off-the-shelf for use in small diameter streamers were bimorph or "bender" units. It was understood that their sensitivity varied as a function of ambient pressure, or tow depth. Unfortunately the sensitivity of the units was also found to change, variably, with use. After a few month's use differences in sensitivity of the transducers ranged from 0 to 20 dB; what was once a continuous-configuration array of relatively uniform sensitivity along its length became a somewhat unpredictable quantity. Experience with these arrays, however, has yielded significant improvements.

Ceramic-cylinder transducers were used in the construction of two new, small diameter (25.4 mm) arrays of 200 elements. Cylindrical transducers were selected because a cylinder is in itself ideally symmetrical and an inherently strong and stable form; the form of transducers used, for example, in a series of reliable secondary-standard hydrophones. Typical of these is the LC-32, made by the Atlantic Research Corporation. A transducer of this type was considered necessary to ensure that the sensitivity of the units along an array would remain uniform over long periods of time. No small ready-made cylindrical transducers for seismic

array use were found to be commercially available on an off-the-shelf basis. A cylindrical unit to be made to our specifications and competitive in price to the bimorphs was sought. Aquadyne Incorporated, of Falmouth, Massachusetts became the successful bidder. An element that could be mistreated, i.e., stepped upon and banged against the side of a ship, was required. Several sizes and materials were tested. A sensitivity of about -100 dBv per μ bar was considered adequate. A lead zirconate titanate cylinder, 25.4 mm in length with a 12.7 mm OD and 1.27 mm wall, was chosen as a compromise in consideration of the requirements of size, sensitivity, frequency response, capacitance, and mechanical ruggedness.

CONSTRUCTION OF THE ARRAY

The mechanical construction of the new array is similar to that described by Prada (1967). The 30-meter-long active part of the array is made up of four 7.5-meter sections each of which has 50 transducers spaced about 152 mm apart. The skin and tensile member of the array is 25.4 mm OD, 3.2 mm wall, polyurethane tubing. The ends of the sections of tubing are wire clamped to aluminum fittings through which pass connecting wires. The sections are joined with aluminum sleeves. A diagram of the array is shown in Fig. 1.

Modifications of and additions to the Prada design include: the new cylindrical transducers; improved oil seals in the aluminum coupling sections; a secondary-standard reference hydrophone; a highly-flexible polyurethane forward-section to decouple the tow cable from the array to reduce the transmission of cable vibrations; a highly-flexible polyurethane tail-section to allow tail-whipping to occur in an inactive and decoupled section; a two-channel preamplifier; and a depth sensor.

The cylindrical transducers are potted in epoxy both to seal the terminals and to protect and increase the strength of the cylinders. The outside diameter of the encapsulated transducers is about 16 mm so that they slide easily into the urethane tubing which has a 19 mm inside-diameter. Three bus-bar conductors pass through each transducer; one is connected to the outer surface of the cylinder, another to the inner surface, and the remaining buss passes through without connections. Extensions of the bus-bar at each end of the transducer

provide inexpensive terminals. The identity of the terminals is shown in Fig. 2. The three-terminal arrangement (a suggestion of F. R. Hess) permits in-line wiring of the elements in parallel, in series-parallel, or in series such that no wires pass over the sensitive surfaces of the transducers. The transducers are connected with finely stranded-#20-AWG, wires soldered to the terminals. Although a complete failure of the array due to a short circuit in a single transducer would be avoided by connecting the transducers in series-parallel, a parallel hook-up has been used in the first model for simplicity.

Transducers for the array are selected to be equal within ± 4 dB in sensitivity. Each transducer is calibrated by comparing its response to that of a known secondary-standard simultaneously subjected to low frequency (10 to 50 Hz) signals in a pressurized calibration tank (Knott, 1967). No appreciable change in sensitivity occurs over the range of ambient pressure to be expected from 0 to 60 meters of seawater. Pressure dependent calibrations have not been extended beyond this point. However, the transducers have been pressure checked to over 3.5×10^7 N/m² (5,000 psi) without implosion. Typical frequency response calibrations measured by the Underwater Sound Reference Division of the Naval Research Laboratory at Orlando, Florida, are shown in Fig. 3.

The 50 transducers of each section are held in their relative positions within the tubing merely by the wires used for electrical connections. These wires are cut about 5 mm longer than required for the 152 mm center-to-center spacing of the transducers. Coiled pairs of wires about 250 mm long are connected to the transducers at each end. When an array section is assembled, the string of 50 transducers is pulled into the polyurethane tubing, and then the tubing is stretched so that it encloses the complete string. The tension on the tubing is then released while the end transducers are held in position. This causes the connecting wires to buckle slightly, thus positioning the array of transducers about 153 mm apart. The coiled wires at the ends of the sections provide enough slack to allow for elongation of the polyurethane tubing under more than 450N (roughly 100 lbs) tension, more tension than that expected under towing conditions. When the array is assembled these wires are spliced to those which feed through the end-fittings. Assembled array sections are connected together by the watertight aluminum sleeves that slide over and fasten to the end-fittings and are sealed by O rings. For further simplicity the array sections are electrically connected by wire-splices which are covered by the sleeves.

Four feed-through wires are put in each end-fitting, although some are used only as spares. An oil seal to prevent leakage of oil from the array sections into the connecting sleeves is made by potting the stranded feed-through wires in polyurethane. A short length of each wire that will lay within the potted section is stripped of insulation and soldered to fill the space between strands. An overhand knot tied in the wire next to the solder-seal anchors each wire in the potting material. When the feed-through wires of the end-fittings are spliced to the array section, the polyurethane tubing of the section is again stretched to facilitate seating the fittings in the ends of the tubing. Once in position the tubing is wire-clamped to the fittings.

Array sections are filled with SAE #10 motor oil (an easily obtained liquid of about .86 specific gravity) by pumping the oil through a small tapped hole in the end fitting. As oil is pumped in one end, the array section is held so that air is displaced towards the other end. The tapped holes are plugged with seal-screws when the section is full.

A section filled with light motor oil has slight negative buoyancy. Neutral buoyancy may be obtained by using combinations of diesel oil, kerosene, gasoline, and possibly other liquids. The motor oil, however, damps the movement of the transducers better than a lower viscosity liquid might. In practice the towing characteristics of an array of slight negative buoyancy is more easily predicted than one that may under certain hydrographic conditions become slightly positively buoyant.

A single secondary-standard hydrophone is mounted in a short (0.5 m) section attached to the forward end of the array. An Atlantic Research Corporation LC-32 has been used, but one of the array transducers properly calibrated would suffice for work allowing a narrower frequency response than that of the LC-32. The calibrated hydrophone is used to relate array signals to absolute signal levels for such measurements as bottom reflectivity.

A limber stretchable forward section about 7.5 meters long connects the hydrophone sections to the depth meter assembly and pre-amplifier case and mechanically decouples the array from the tow cable and preamplifier case. The polyurethane tubing used for this section has a durometer of 70 compared to the 78 to 80 durometer of the stiffer hydrophone sections. Two small coaxial leads (RG-122U) are coiled in the tubing to connect the array and secondary standard to the preamplifiers.

The coaxial leads are long enough to permit the forward section to stretch 1 1/2 times its normal length under about 450N (100 lbs) tension. When filled with #10 oil this section also has a slight negative buoyancy.

The forward section has proven worthwhile in reducing low frequency (about 10 Hz) noise that has been associated with cable strumming. An even longer forward section or provision for more elongation appears to be required at speeds approaching 10 knots. The wire leads of one of the two forward sections made for the two arrays became taut under a little less tension than the other; the array towed with this section was consistently noisier at high speeds.

The coaxial leads are connected to the hydrophone and preamplifiers via the small feed-through wires in the same type of end-fitting. It is particularly important therefore to secure the ends of the coiled coaxial leads to the end-fittings so that the strains of tension and vibration will not break the small wires. The method currently used is shown in Fig. 4.

A 7.5-meter length of the limber, 70 durometer, 25.4 mm tubing is also used for a tail-section. This liquid filled, highly-flexible section is being tried as a means to force tail whipping to occur in an inactive section mechanically, by its own limberness, decoupled from the array. Liquids of lower specific-gravity than fresh water cannot be used because the tubing is close to neutrally buoyant in seawater. When filled with fresh water, the section is positively buoyant. The required slight negative buoyancy has been obtained by using an ethylene-glycol solution (about 1.02 specific gravity) which also partially eliminates the problem of freezing. Other water-solutions and liquids could be used. A 15 m braided nylon-rope tail is fastened to a stream-lined PVC plug at the end of this section.

An absolute pressure potentiometer located in a short oil-filled hose between the preamplifier case and array assembly provides continuous measurement of tow depth. The depths measured by this system can be compared with depth determinations made by observing the delay between directly received and surface reflected seismic signals picked-up by the secondary-standard hydrophone. Static calibrations of the pressure potentiometer assembly are made by subjecting the complete assembly to known pressures in a testing tank.

The end-fitting between the depth meter section and preamplifier

case requires seven feed-through leads, three for the potentiometer and four for the two hydrophone systems. Common grounds may be used if a lead should become defective. The wires are sealed in this fitting with urethane potting compound as before.

Since there are two hydrophone systems, the array and the secondary-standard, a two-channel preamplifier is required. Identical stable operational amplifiers with 20 dB gain have been used in each channel and an electronic calibration circuit is included. Although the preamplifier circuit shown in Fig. 5 is currently in use, many other circuit arrangements may be used. The preamplifier case is similar to that used by Prada (1967).

RESULTS

The two ceramic-cylinder arrays have been used successfully for several months at sea. Calibrations of the transducers repeated over a month's time before assembly of the array have shown stable results. Measurements of the sensitivity of ten transducers a year later show an average difference between the two calibrations of 0.5 dB. The spread of the differences between the two calibrations is 0.1 to 1.0 dB.

Acoustically the arrays have performed very well. No special care in handling has been given the arrays at sea. The signal-to-noise ratio over the broadband of interest while towing at speeds from 5 to 10 knots from the R/V CHAIN is equal to or superior to any array used at Woods Hole for CSP or similar work. Noise from all sources when operating in moderate seas (sea state 2-3) is commonly at so low a level that only occasional "tinkles" typical of near surface ambient noise are heard when listening broadband at a tow-depth of 10 meters and at speeds of 6-8 knots. When seismic reflections are received by summing the outputs of these two arrays, towed simultaneously at about 8 kts (Knott and Bunce, 1968), the deeper reflections (2 to 3 sec. two-way travel time below the seafloor) can be recorded graphically broadband (20 to 1000 Hz) with no appreciable background noise. However, the need to detect possible structures buried more deeply than those easily seen on the records requires that gains be increased to the limit set by the signal-to-noise ratio, thus there will rarely be a time when a "no background" condition exists. The signal-to-noise of the secondary-standard hydrophone is also improved. Seismic reflections received by this single hydrophone at towing speeds of 6-8 kts can be analyzed over a frequency range of about 100 Hz to several kHz.

SUMMARY

Not only are more clean-cut and useful CSP data obtained by following the continuous configuration approach and employing the other design features described here, but taking these data is far easier than with the more cumbersome arrays. Higher towing speeds and thus more areal coverage have been attained. High sea-states now limit ship operation before they limit profiling capability. A copy of an original record taken in sea-state 5 to 6 by K. Prada and R. Oldale is shown in Figure 6. The reception of ship's propulsion and general machinery noise has been minimized particularly by the improved directional response of the array. The unambiguous directivity of the array also enhances the reception of the seismic signals. The equality and stability of the transducers ensures that the response of the array will be maintained. Relatively short towing cables can be used without detriment. Towing-cable vibration is damped by the combination of a woven tensile member and a covering of flotation foam of low elasticity. Noise either generated or propagated by the towing-cables is effectively decoupled from the arrays by the limber, stretchable forward section of the array assembly. In addition, the array transducers are minimally restrained and thus are themselves decoupled from the array's skin and tensile member.

Future array designs will, no doubt, produce greater signal-to-noise ratios. At present, however, it appears that further improvement, other than the summation of more than two arrays, will be most easily attained by employing more powerful broadband sources.

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1. MULTICONDUCTOR TOW CABLE WITH WOVEN STRAIN MEMBERS AND FLOATATION
2. PREAMPLIFIER CASE
3. OIL-FILLED HOSE ENCLOSURE FOR DEPTH METER
4. LIMBER AND STRETCHABLE FORWARD SECTION , 7.5 METERS LONG
5. LC-32, REFERENCE HYDROPHONE SECTION , 0.5 METERS LONG
- 6,7,8,&9. ARRAY SECTION EACH 7.5 METERS LONG & CONTAINING 50 TRANSDUCERS
10. LIMBER LIQUID-FILLED TAIL SECTION
11. BRAIDED NYLON ROPE-TAIL

Figure 1. Diagram of the 200x ceramic-cylinder array.

Figure 2. Terminal arrangement and schematic of the AQ-1 transducer.

NOTE: OMNIDIRECTIONAL WITHIN 0.5dB IN HORIZONTAL (XY) PLANE.

Figure 3. Frequency response of three AQ-1 transducers, measured by the Underwater Sound Reference Division of the Naval Research Laboratory, Orlando, Florida. (One of the group sent to Orlando was purposefully of different sensitivity to check the calibration facility at Woods Hole.)

Figure 4. A method of relieving tension on the interconnecting feed-through wires in the stretchable forward section of the array.

Figure 5. 200x ceramic-cylinder array, preamplifier and cabling diagram.

Figure 6. A seismic profile taken in sea state 5 to 6 with a single 200x ceramic cylinder array and an underwater spark at about 55kJ, stored energy, Passband 18.7 to 70 Hz.

PART II

A COMPARISON BETWEEN THE RESPONSES OF A CONTINUOUS LINE ARRAY AND A DISCRETE LINEAR ARRAY

by

R. T. Nowak

The purpose of this section is to illustrate the difference between the response of a linear array of discrete hydrophones and the response of a line hydrophone which is continuously sensitive along its length.

For simplicity, the sound field will be that due to a plane wave of fixed frequency (f). In such a wave the surfaces made up of points of equal acoustic pressure at a prescribed instant of time, i.e., the wave fronts, are planes and the wave moves in a direction perpendicular to these wave-fronts. If such a wave is "frozen" at some instant of time, the variation of pressure along a line parallel to the path of the wave will have a sinusoidal nature as shown by the solid-line curve in Figure 1. The distance between points of equal acoustic pressure along the line of propagation is the wave length λ . The same wave, frozen at a time Δt later, will have moved to a new position a distance $c\Delta t$ away, as shown by the dashed-line curve, where c is the "sound velocity". In one period of the signal or a time $T = 1/f$ the wave will move one wave length so $c = \lambda f$.

The variation of acoustic pressure with time at one point in the medium is shown as the solid-line curve in Figure 2. If the variation of pressure with time at another point near the first is plotted, there is a phase difference between the signals given by $\Delta\phi = \frac{2\pi\Delta x}{\lambda}$ as shown by the dashed curve of Figure 2. The separation of the points, Δx , is along the line parallel to the propagation direction. In Figure 3 a plane wave propagating in the plane of the paper is shown with lines designating the wave fronts of maximum and minimum acoustic pressure. In this sound field is a line hydrophone of length L arranged with its axis in the plane of the paper at an angle θ to the propagation direction of the sound wave. The sensitivity of the hydrophone is taken to be $1/L$ units of output per unit length per unit of acoustic pressure. In a situation where the hydrophone is subjected to a varying acoustic pressure along its length its output is the sum of the response of each small section with the result,

$$\text{OUTPUT} = \frac{\sin \frac{\pi L \cos \theta}{\lambda}}{\frac{\pi L \cos \theta}{\lambda}} \sin 2\pi f t$$

The factor, $\sin 2\pi f t$, expresses the fact that the output from the array has a sinusoidal variation in time of frequency f . The amplitude factor

expresses the dependence of the output on the orientation of the hydrophone with respect to the moving acoustic wave and on the relation between the length of the array and the acoustic wave length. In order to illustrate this dependence a number of situations are examined in the following figures. In Figure 4 the acoustic wave length is equal to the length of the array and the angle θ is varied between zero and ninety degrees. In Figure 5 the wave length is one half and Figure 6 one fifth the length of the array. The trend here is obvious, as the ratio of array length divided by acoustic wave length increases, the response decreases more quickly as the angle θ departs from 90° .

In comparison, the response of a linear array made up of N hydrophones separated from each other by a distance ℓ is examined. The total length is equal to $L = (N-1)\ell$. The response of the array is obtained by adding the signals from each hydrophone to obtain an equation similar to the one for the line hydrophone. This may be shown to have the result:

$$\text{OUTPUT} = \frac{\sin N\pi\ell\cos\theta/\lambda}{N \sin \pi\ell\cos\theta/\lambda}$$

As an illustration a five element array was chosen and four situations have been plotted: $\lambda = L$, $\lambda = L/2$, $\lambda = L/4 = \ell$, and $\lambda = L/8 = \ell/2$ (Figs. 7, 8, 9, 10). The plots for $\lambda = L$ and $\lambda = \frac{L}{2}$ are seen to have a behavior which is similar to the corresponding plots for the line hydrophone in that the response generally decreases as the angle θ departs from 90° . The plot for $\lambda = \ell$ is different however because the response rises to its maximum value again at $\theta = 0^\circ$ when the wave length is equal to the spacing between hydrophones. The plot for $\lambda = \frac{L}{8}$ shows two angles other than 90° at which the response is a maximum. It can be shown that there will be a number of maximum response peaks equal to the number of acoustic wave lengths which will fit in the spacing between the hydrophones.

When the frequency is varied at a fixed angle of incidence, the response term for the line hydrophone may be rewritten:

$$\text{OUTPUT} = \frac{\sin \left(\frac{f}{f_0} \pi \cos \theta \right)}{\left(\frac{f}{f_0} \pi \cos \theta \right)}$$

where f_0 is the frequency of sound which will have an acoustic wave length equal to the length of the array. If for example the array is 100 meters long and the velocity of sound is 1500 meters per second, f_0 is 15 Hertz. The frequency response curves have been plotted in Figure 11 for angles of $\theta = 90^\circ$, $\theta = 84^\circ$, $\theta = 60^\circ$, $\theta = 0^\circ$.

Frequency response curves for a five element discrete array have been plotted for the same angles of incidence in Figure 12. The response function for the discrete array is:

$$\text{OUTPUT} = \frac{\sin \left(\frac{5}{4} \pi \frac{f}{f_0} \cos \theta \right)}{5 \sin \left(\frac{\pi}{4} \frac{f}{f_0} \cos \theta \right)}$$

Here f_0 is the frequency of the sound having a wave length equal to the array length which is four times the spacing λ .

In summary the comparison shows the following principle differences between the two types of arrays.

1. At a fixed frequency the trend of the response of the line hydrophone always decreases as the angle of incidence of the sound departs from normal incidence, but the discrete array may produce peak response at angles of incidence other than at 90° .

2. For a fixed angle of incidence other than 90° the response of the continuous array generally decreases as the frequency is increased, but for the discrete array the response may peak at frequencies other than zero.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Figure 7.

Figure 8.

Figure 9.

Figure 10.

Figure 11.

Figure 12.

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Reference No. 69-12

PART I. A CONTINUOUS CONFIGURATION HYDROPHONE ARRAY FOR BROADBAND CONTINUOUS SEISMIC PROFILING by S.T. Knott. PART II. A COMPARISON BETWEEN THE RESPONSES OF A CONTINUOUS LINE ARRAY AND A DISCRETE LINEAR ARRAY by P.T. Nowak. 27 pages. April 1969. Contract Nonr-4029(00), NR 260-101.

The signal-to-noise ratio of towed receivers employed in seismic reflection profiling is significantly improved by using a hydrophone array whose broadband directional response approaches that of a theoretically continuous sensor. Within a broad pass band all secondary lobes of an array of continuous configuration are less sensitive than the main lobe. This design improves upon the directivity and thus the signal-to-noise ratio realized in broadband work by those linear arrays in common use whose transducers are spaced widely compared to the wavelength and duration of transients of acoustical noise projected along the array from all angles of reception. Sensitivity equal to that of the main lobe is developed by the secondary lobes of these commonly used arrays at various frequencies and angles to the array.

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1. Towed hydrophone arrays
2. Continuous seismic profiling
3. Continuous configuration line arrays
4. Signal-to-Noise Ratio of Towed Arrays
5. Directional response of linear arrays

- I. Knott, S. T.
- II. Nowak, R. T.
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