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AN ULTRASONIC AIR-ACOUSTIC APPARATUS FOR THE DEMONSTRATION OF ARRAY THEORY

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INTRODUCTION

In teaching array theory within an underwater acoustics course there is a requirement for supporting demonstrations and experiments. A typical example is the investigation of the directivity pattern of a multi-element linear array which would involve the comparison of theoretical and practical plots. When carried out in a test tank, such demonstrations whilst producing representative results, fail to provide the accuracy for an unqualified and convincing verification of the associated theory. This is particularly noticeable when investigating directivity patterns at angles approaching 90°; there are many possible causes such as questionable baffle conditions, housing diffraction effects, non-inert mountings etc.

It is the author's opinion that such demonstrations should nto be attended by the necessity for qualifying explanations of complicated phenomena which are not immediately relevant and are likely to confound the student. It is on this premise that the demonstration apparatus was developed.

Classical texts introduce basic array theory on the supposition of point sources located at the centre of an infinite, rigid and inert baffle. If the basic theory is to be demonstrated without qualification then attention must be given to obtaining or at least approaching the suppositions mentioned. In this context a rigid baffle is a perfectly reflecting surface and the approach to a rigid baffle is significantly easier in air than in water. A consideration of the acoustic impedance of air, water and common structural materials will confirm this statement. Operation in air also simplifies the other design objectives of obtaining an effective infinite and inert baffle.

In developing the facility the major effort has been addressed to the acoustic problems, leaving the associated electronics and display as adequate for the purpose but in need of enhancement.

In its present form the facility consists of a 1.2 metre square table serving as a baffle at the centre of which is a linear array of seven independently controlled transmitting point sources. A hand rotated gantry pivoted at the baffle plane carries a single receiving transducer which allows the array field to be investigated over a displacement of ± 88° from the acousti- axis, Fig 1 is a general view of the facility which also shows the associated electronic instruments and units. Each source has an on-off switch and electronic controls for setting the source amplitude and phase, by this means, any combination of sources may be selected for form different arrays for the demonstration of uniform and tapered array theory.

The transducers have a resonant frequency of 44 kHz and are operated in a pulsed mode in order to eliminate the problems of reverberation and interfering echoes from the immediate structure. From the receiving transducer the signal is passed via a 60 dB amplifier to a dual time-base oscilloscope which displays a range-gated portion of the pulse as a sine wave. The associated gantry angle is shown as a reading on a digital voltmeter.

System signal-to-noise is better than 50 dB and by careful adjustment of source amplitude and phase, directivity pattern nulls of 45 dB are revealed.

DETAILED DESCRIPTION

The transducers

Two forms of seven element array were produced, the first being a relatively simple construction employing one transducer, served as a means of assessing the potential of the proposed facility. The second, having seven separately controlled transducers gave improved results and extended the investigations to tapered arrays and beam-steering.

In selecting a transducer the first requirement was for an operating frequency out of the sonic range so as to eliminate the problems of operating nuisance and sufficiently high that the general laboratory background noise would not adversely affect the demonstration. The second requirement was for a practical wavelength ie one that would not require a large structure which would be out of place in a laboratory. Proprietory 40 kHz transducers as used for TV controllers and alarm systems were readily obtainable however their diameter, being 16 mm (approximately 2λ), precluded their direct use in a linear array of seven elements intended to have no diffraction secondaries. In the absence of any other suitable transducer it was decided to use them in some modified form so as to allow a source spacing of less than λ.

A requirement common to both forms of array was that however housed, there should be no direct structural borne sound making the baffle other than inert.

The single transducer array

An investigation showed that radiation from a 1 mm diameter aperature produced an adequate signal level at the receiver. From this result it was decided that a suitable array would be a linear arrangement of seven 1 mm holes pitched at 5.5 mm (1 mm = $\lambda/8$ which is a good approximation to a point source).

The protecting mesh across the radiating aperature of the transducer was removed and replaced by a plate having nine holes set out on a circumference of approximately 12 mm. Silicon rubber tubes of 2 mm bore and 50 mm length were used to connect the transducer to a coupling block into which the 1 mm diameter sources were drilled. Connections to the block were made via trombone type slide adjusters allowing the acoustic length of each transmission path to be adjusted for equal phase at the source. Additionally, the block was fitted with adjustable constrictions so as to afford a means of setting the sources for equal amplitude. A view of the interior of this arrangement is shown in Fig 2.

The array has the attraction of simplicity in that a single line drive only is required and no special demand is placed on the frequency stability of the drive oscillator. Furthermore, drive level changes do not result in source phase differences as would be the case for a multi-transducer solution with its attendant imperfections. The principal difficulty with this single transducer array is the rather tedious mechanical procedure when setting up for equal phase and amplitude at the sources. When making source amplitude adjustments there is a noticeable interdependency between adjacent controls. This problem is thought to be caused by a mis-match between the coupling tubes and the variable constrictions in the coupling block. Standing waves are set up which interact at the points where the tubes terminate in the transducer to produce a degree of mutual coupling.

During the setting up procedure it was observed that heat radiation from the hands, affecting one tube more than another, produced a noticeable phase difference at the sources. As a result of this observation the array assembly was double cased to minimise phase shift when handling the array housing.

The defects mentioned above make the single transducer array totally unsuitable for tapered drive demonstrations.

As a consequence of the silicon rubber coupling tubes and the use of plastic foam material for a transducer bedding, structural borne sound is undetectable and there are no problems due to direct coupling between adjacent sources.

Arrays of less than seven elements may be investigated by the simple process of blanking unused sources with strips of PVC electrical tape, this technique reduces the source output to below the receiver noise level. The array housing is readily detached allowing other configurations to be investigated and may be rotated to obtain field patterns in any plane.

The multi-transducer array

A major problem in producing a multi-element array is the inevitable performance dissimilarities of proprietory 40 kHz transducers. Ideally the transducers should have identical resonant frequencies unaffected by the drive level changes required when tapered array demonstrations are conducted. Furthermore, it would be desirable that the transducers have identical phase-frequency characteristics such that pre-set source phase conditions would not be affected by the frequency drift of a simple oscillator. These ideal properties are not found in proprietory transducers.

As for the single transducer design, it is required that a seven element array be designed having no diffraction secondaries. The problem of 16 mm diameter transducers conflicting with a requirement for the sources to be pitched at 5 mm was solved by re-mounting the piezo-electric elements into a 10 mm diameter tube fitted with an exponential horn. A cut-away drawing of the arrangement is shown in Fig 3a and the assembly of units forming the seven element array in Fig 3b.

With reference to Fig 3a the bilaminar ceramic element operates in a vibrational mode having one nodal ring of approximately 4 mm. The perspex mount has a tubular extension of this diameter to which the ceramic is attached by RTV silicon rubber and is grooved to accept the connecting wires. The mount assembly is a sliding fit in the tubular body to provide a means of coarse phase adjustment. Prior to assembly the ceramics were adjusted by grinding to bring their resonant frequencies to a common value, a nominal 43.8 kHz. This frequency was chosen to give a kd value of unity where d is the source spacing of 5 mm.

The choice of an exponential rather than a conical horn was based on the fact that the former provides a better match and lends itself more readily to the mechanical manipulation necessitated by the conflicting source spacing and transducer diameter.

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The horns were produced by wrapping a shaped length of 0.15 mm thick aluminium sheet around an exponential mandrel, the overlap joint being set by the application of cyano-acrylate adhesive.

The receiver transducer

Since the ceramic and cone had to be retrieved from the 40 kHz transducer in order to effect an increase of resonant frequency to 43.8 kHz the opportunity of re-housing the assembly to form a totally screened receiver stalk was taken. This virtually eliminated electrical noise pick up.

System rise-time and facility dimensions

For this application a most important parameter is the combined rise-time of the transmitter and receiver as this will dictate the dimensions of the apparatus. From the transducer specifications a rise-time of 2 ms was predicted whilst the practical value was found to be about 0.75 ms, it is questionable whether the grinding and remounting of the ceramic contributed to the reduction. Based on the measured value, a pulse duration of 1.5 ms was necessary which equates to a physical length in air of 0.5 metre which in turn dictates that the minimum path length between the receiving transducer and any part of the structure must be at least 0.25 metre.

System block diagram

General purpose laboratory instruments together with several purpose-built units are connected to form a conventional pulsed system as depicted by Fig 4. The receiver pulse is displayed on a dual time-base oscilloscope, the delayed time base and associated control being used as a range gate to select out a specific cycle of the receiver pulse for amplitude measurement. The SYNC input to the Transmitter Pulse Generator ensures that the oscillator output is coherent with the leading edge of the transmitter pulse giving a more visually acceptable display. In order to combat the different phase/frequency characteristics of the individual transducers an oscillator with a frequency stability better than 1 in 10^4 is necessary.

The block diagram does not show the simple circuitry of the gantry angle indication. This consists of a servo-quality potentiometer driven from the gantry pivot, the potentiometer being supplied from a dc source sufficient to develop an output of 0.1 volt per degree. A digital voltmeter is used as a display.

Amplitude and phase adjustment procedure

If good results are to be obtained some care must be used in setting up the amplitude and phase of the selected sources. Whilst other more accurate methods are possible the procedure adopted in obtaining the published results is considered to be adequate and is uncomplicated. The gantry angle is first set to 0° and a single source is selected, the prescribed amplitude is set and the sine wave positioned to the graticule centre by means of the X shift controls. This source is used as a phase reference when setting up the remaining sources.

By this method, judicious use being made of the oscilloscope expansion controls, it is possible to set the amplitudes to better than 1% and phases to about ± 3% of the required values.

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RESULTS

Some indication of performance expectation is provided by the directivity pattern of an isolated source. A source diameter of 1 mm operating at a frequency of 43.8 kHz has a ka product of 0.4, where 'a' is the source radius. At 90° the theoretical response is -0.26 dB relative to a perfect point source. Investigation of an isolated source over the full range of angles produced no error greater than -0.56 dB thus the maximum error of the practical source is 0.3 dB.

In this short paper there is insufficient space to show the results obtained using the single transducer array. Directivity patterns for two, three, four and seven element arrays were produced and used to demonstrate the theory, particular attention being given to theoretical and practical beam widths and the angular positions of diffraction secondaries. The plots were in polar form and departed from theory by no more than 2.0° in angle and 3.0 dB in amplitude.

With its improved amplitude and phase control the results obtained using the multi-transducer array were superior, two sets of results in Cartesian form are shown in Fig 5. The figure shows the directivity patterns of an array of seven point sources, one relating to a uniform array and the other to a 30 dB Dolph-Chebyshev tapered array, practical results are superimposed as measured points.

It is suggested that the very accurate results of the uniform array relative to the tapered array may be linked to the procedure used in setting up the source amplitudes and phase conditions. When setting up the tapered array, the oscilloscope is in a measurement role, whilst for the uniform array its role is that of a comparator, as such, the accuracy in matching the amplitudes is at least an order better since the absolute accuracy of the oscilloscope is irrelevant.

CONCLUSIONS

The principal objective of designing an array theory demonstration of superior performance to that of its underwater equivalent has been achieved. Being in the development stage, there is considerable scope for both improvement and enhancement, a first priority being the introduction of a plotting facility with a Cartesian and a polar capability.

Some improvement in dynamic range is possible by replacing the preamplifier, which has a rather low saturation level of 1.5 V, by one which would allow the full output of the transducers to be realised. There may be a limit to this exercise due to random air movement which manifests itself as a low frequency disturbance on the display.

As a final comment it is suggested that the apparatus may have applications as an aid in the design of arrays.

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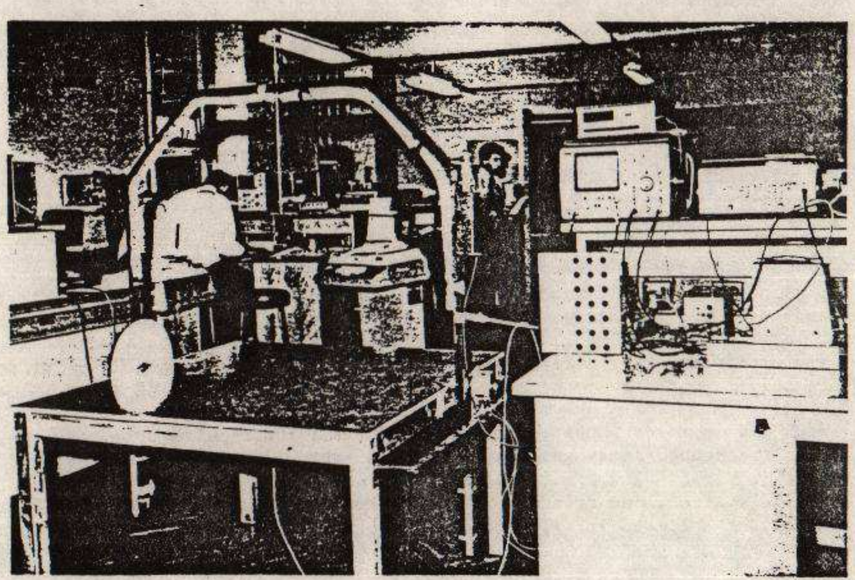

Fig 1 The apparatus and associated instruments

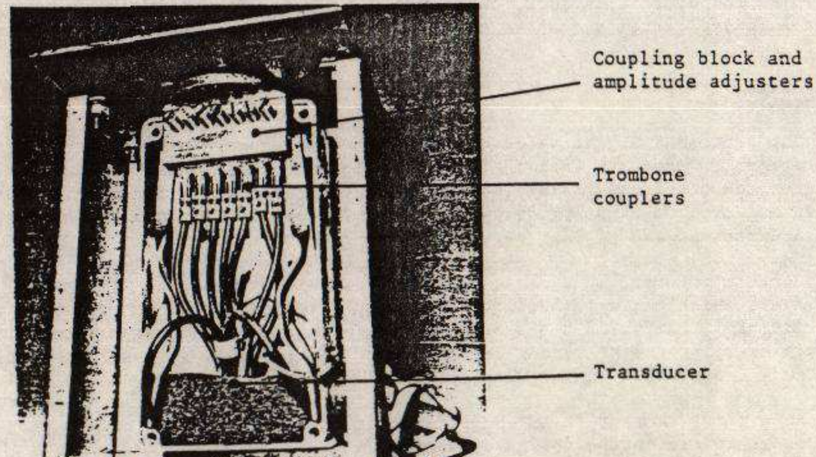

Fig 2 Seven element single transducer array

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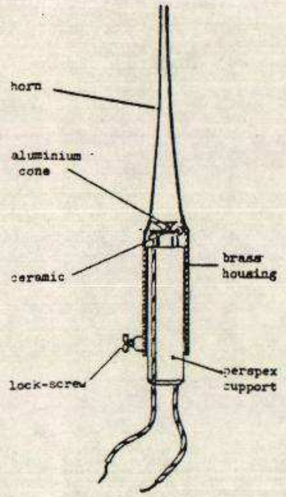

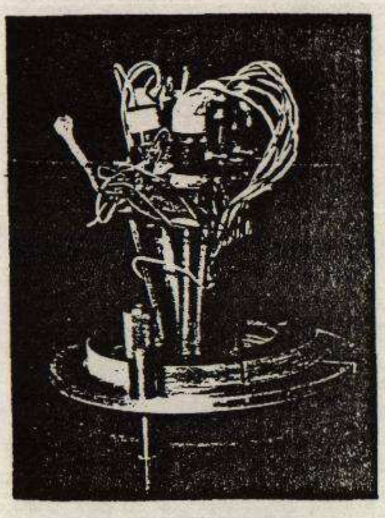

(a) The transducer (b) The array assembly

Fig 3 Seven element multi-transducer array

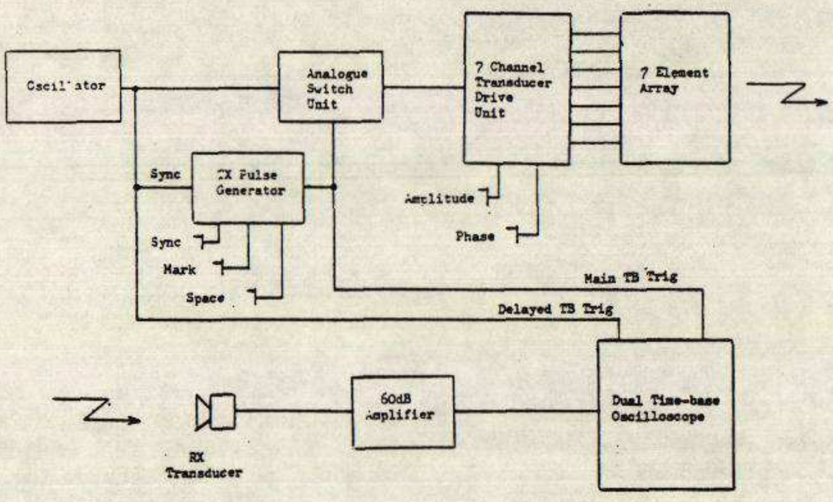

Fig 4 System block diagram

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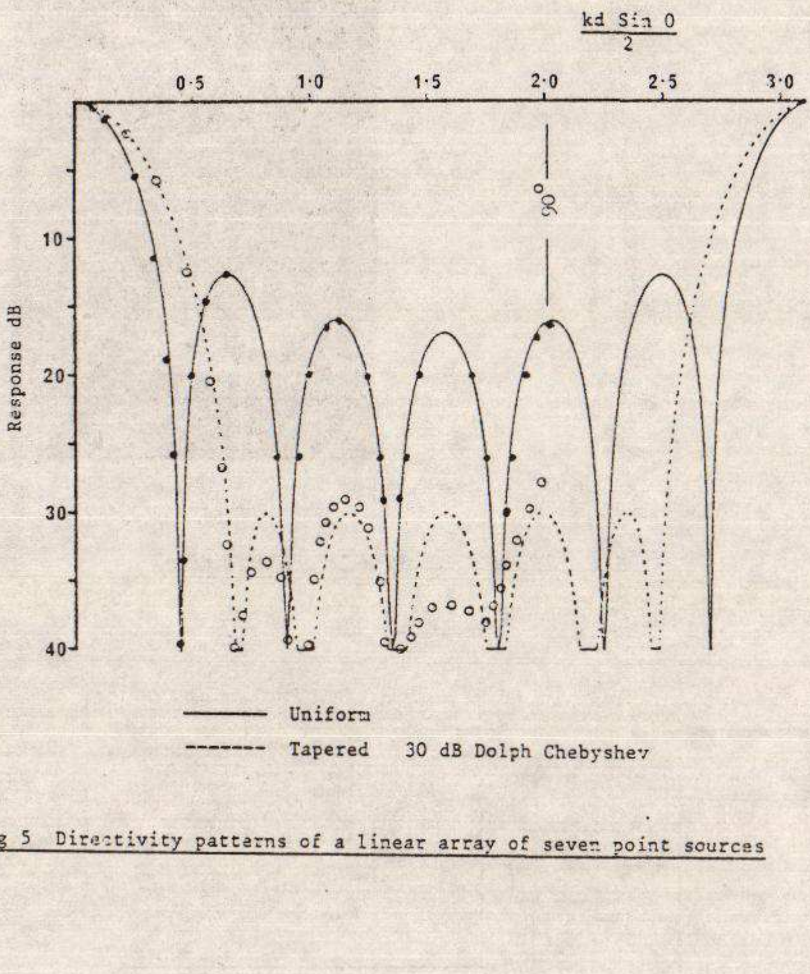

Fig 5 Directivity patterns of a linear array of seven point sources