A Constant-beamwidth Log-periodic Planar Array

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1.0 Introduction

This paper describes the development of a new receiving array for the Wide Band Sonar. This is a sonar system in which the carrier frequency in the water can be varied over a very wide range, for example a ratio of 10:1 from the highest frequency to the lowest. The general application is in the investigation of the echoing strength of targets, such as fish or the sea bed, as a function of frequency, leading perhaps to identification of classification of unknown targets. A constant beamwidth on transmission has been obtained with a non-linear (parametric) source, in which the wanted low frequency signal in the water is obtained by the interaction of two high-frequency waves, and a similar directional response is now needed on reception. Since it may be difficult to control the exact position of the target relative to the array, it is highly desirable that the directional pattern as well as the half-power beamwidth should remain invariant with frequency, so that the apparent variations in target strength are not caused by changes in the pattern.

One class of constant-beamwidth arrays depends on the geometrical shape of the surface of the array, perhaps with a fixed amplitude taper invariant with frequency (1, 2, 3). These can be designed to have suitable directional responses, but they suffer from the disadvantage that, if they are made up of a number of discrete non-resonant transducer elements, the spacing between these is set by the highest frequency of operation, whereas the overall size is set by the lowest. Hence for a wide range very large numbers of elements are needed, and for a planar array the number is proportional to the square of the frequency ratio. The alternative scheme is to vary by electrical filters the active size of the array inversely with frequency, so that the size in wavelengths remains constant; the spacing between elements can be varied so that efficient use is made of fewer of them. A two-section linear array has been described (4), and the present scheme is an extension to a planar array covering a wider range.

2.0 Theoretical aspects

2.1 The general scheme

The desirable features of a constant-beamwidth array can be provided, at the cost of the complex associated electrical circuits, by a log-periodic structure in which the dimensions follow a geometric progression. A circular planar form is used, since a conical beam shape is preferred. The central core alone is used at the highest frequency of operation, and for the lower frequencies the outer parts are progressively brought into action by the selectivity of low-pass electrical filters. The critical frequencies follow inversely the same geometric progression as the linear dimensions, so that the effective size in wavelenghts remains constant and so does the shape, and therefore the directional pattern should remain virtually constant independent of frequency. For practical reasons a finite number of discrete elements is used, and so there will be periodic variations in the pattern as well as larger errors at the ends of the range due to the mechanical truncation of the geometric progression. These can be minimised by careful choice of the common factor in the progression and the attenuation of the filters in the cut -off region.

If the radial and tangential spacing of the elements follow the same progression, for each proportional increase in size of the array, a fixed number of elements is added, and so this type of array is highly cost-effective in numbers of elements for a wide relative bandwidth. At any particular frequency the outermost effective elements are arranged to be spaced at half-wavelength intervals, this being the optimum sampling density in an acoustic field; elements nearer the centre are closer, which has no acoustic advantages, but the arrangement of the filters is simpler. For the applications envisaged for the Wide Band Sonar, a circular beamwidth of about 15° to 20° between half-power points is suitable, and so the effective diameter should be about 3λ and the number of elements in each ring for 0.5λ spacing would be 18.

2.2 The acoustic design

In constructing the array, the rings of elements have been made hexagonal rather than circular for mechanical convenience, the directional response near the main beam showing negligible differences from that for circular rings. The core of the array, the only part active at the highest frequency for constant beamwidth, consists of 19 elements, evenly spaced 0.75λ apart on a hexagonal grid. The next ring on the same grid has 18 elements, but the overall diameter becomes 4.5λ instead of 3λ for the core alone at the design frequency for the latter. This 37 element array would have the same beamwidth as the core at a design frequency two thirds of that for the core, and this leads immediately to a value of 1.5000 for the constant factor in the geometric progression of dimensions.

The elements in the core are spaced by more than the optimum half wavelength at the highest frequency, but the only disadvantage is that the sidelobe levels well away from the main beam are increased a little; however there is a small saving in the numbers required.

The relative range of frequency for constant beamwidth is 1.5^N, where N is the number of rings outside the core. For the specified range of 6 to 60 kHz N = 5.68; the next lower integer was chosen for the array actually built, giving a range from 7.90 to 60 kHz. The useful range can be extended easily by adding more rings and the associated filters. Outside the innermost 37 elements the sampling density in space is reduced, and hence the sensitivity of individual rings of elements must be progressively increased outwards. The appropriate factor can be estimated in various ways, but the most logical is by equalising the beamwidths at the design frequencies. The average value so found is very close to 2.00, so that for each 18 element ring outside the first, the relative contribution to the final output must be doubled in succession. In the complete system the amplitudes are to be adjusted for minimum variation in beamwidth.

2.3 The electrical design and theoretical beamwidth

Each ring has its own low-pass filter, with the cut-off frequency just above the design frequency; the central core does not need such a filter, except to improve the rejection of high-frequency noise. The basic design of all the filters is the same, with the frequencies scaled appropriately. Ideally each filter has no loss at the design frequency of its ring and infinite loss at the next higher design frequency; the characteristics in between are calculated for constant beamwidth. On this basis the beamwidth, about 19°, is shown in fig.1 as for discrete equalisation at the design frequencies and the geometric means between adjacent pairs for N = 7. A more realistic approach is to assume a small loss at the design frequency and a small contribution at the next higher, and this leads to a slightly narrower beamwidth, about 17°, also shown in fig.1 for continuous equalisation. The effects of truncation and the assumed doubling of sensitivity for each added ring are shown by the small trend to narrower beamwidths at lower frequencies. A sample series of calculations between the marked points near the high frequency end, assuming a likely loss curve for the filters, indicated a variation of $\pm \frac{1}{2}^{\circ}$ in beamwidth.

For these calculations, it was assumed that all signals were exactly in phase. In practice this would not be so unless all the filters had exactly the same time delay. They are designed to have a constant delay over their own pass-band, but this is inversely proportional to the design frequency, and therefore there are different delays in the various sections. These are compensated by delay equalisers having flat amplitude/frequency characteristics; however the delay need not be constant over the whole pass-band of the array, only over that of the filter being compensated; this simplifies the design considerably, particularly for the lower frequencies. The overall scheme is shown in fig.2; additional features are an input low-pass filter in each channel and an overall amplitude equaliser to compensate for the increasing sensitivity at low frequencies.

3.0 Practical aspects

3.1 The mechanical design

The basic structure is a flat framework machined out of sheet material, somewhat reminiscent of a spider's web, but expanding in size away from the centre and considerably more solid. The sensitive elements are piezo-electric ceramic tubes 12 mm. long, individually encapsulated in epoxy resin and mounted on a short stainless steel tube. Two sizes are used, 6 mm. diameter for the core and the first ring, where they are at 16 mm. centres, and 12 mm. diameter elsewhere, as there is more space and the larger, more sensitive, tubes can be used. The elements in each ring are connected in parallel, a more reliable way than the series connection. The tubes stand away from the mounting plane by about 35 mm., and this is not a successful arrangement due to reflections from the frame. The worst effects were overcome by filling the space immediately behind the elements with a lossy partially reflecting mixture, but there were also significant reflections from a protective framework, the front part of which had to be removed. The result of these unwanted reflections is that the sensitivity of the rings varies appreciably with frequency, though generally with fair correlation. This defect is bound to have an effect on the constancy of beamwidth, but results obtained are fairly satisfactory after adjustments have been made to the gains in the various channels.

3.2 The electrical design

The filters which control the beamwidth have a requirement which is uncommon, this being that the phase response has to be controlled right through the cut-off region. The general and more precise method is to design a filter to give the required amplitude response with little regard to the phase, and then to add a phase correcting equaliser. This requires much calculation and the circuits may need a large number of elements. The alternative scheme is to use a type of filter which has a good phase response but a less than ideal amplitude response. The latter approach was used, and the resulting filters are fairly simple and easy to set up. The theory of the linear-phase low-pass filter was developed by Bode and Dietzold (5) and a practical design was described by Weaver (6). Because the minimum loss in the stop-band is only 16 dB., two basic filter sections have to be used with their cut-off frequencies offset to give a minimum loss of 34 dB. The insertion time delay of the combined filter has a variation of $\pm 2\%$ up to the first attenuation peak, corresponding to a maximum departure of phase linearity of about 1% when the insertion phase shift approaches 800°. The amplitude response is not quite ideal, being more gradual near the ring design frequency than required and becoming too steep, but this is not necessarily serious, because of the errors caused by the varying sensitivity of the rings. The time delay correctors were designed using the calculated delays in the various filters; they are three or four section second-order active RC networks. No adjustments for phase are included, but the differential phase errors between channels are generally within $\pm 5^\circ$ over the necessary bandwidth.

4.0 Practical results with the complete array

After the mechanical structure was built and before the electrical system was designed, a series of tests was carried out with discrete equalisation. The outputs of the sections were combined directly, the taper functions being set separately for each of the six design frequencies and the five intermediate frequencies by connecting each section through a series capacitor (the electrical impedance of theelements is closely approximated by a capacitance at frequencies well below the lowest resonance of the piezoelectric tubes, about 160 kHz for the 6 mm. ones and 80 kHz for 12 mm). The series capacitances were calculated taking into account the actual sensitivities at the relevant frequencies. The measured beamwidths, shown in fig.3, agree moderately well with the design figure of 19°, but no effort was made at this stage to obtain better results by adjusting the relative contributions. The directional patterns were also acceptable.

The adjustment of the relative contributions for continuous equalisation is not so straightforward, since it applies to all frequencies equally, whereas the individual variations are not entirely correlated. The first set of adjustments was to make the average differences between adjacent rings equal to the design figure of 6 dB. (excluding the ranges of frequency in which the filters are cutting off). The measured beamwidths are also shown in fig.3, and this indicates that further adjustments is required; in particular it appears that the second ring is contributing much less than it should, since the rate of increase of beamwidth just below 40 kHz corresponds to an array consisting of the core and the first ring alone. At the low frequency end the narrow beamwidth of $15\frac{1}{2}^\circ$ indicates that the outermost ring is contributing too much. The directional patterns are very similar to those for discrete equalisation at all frequencies.

5.0 References

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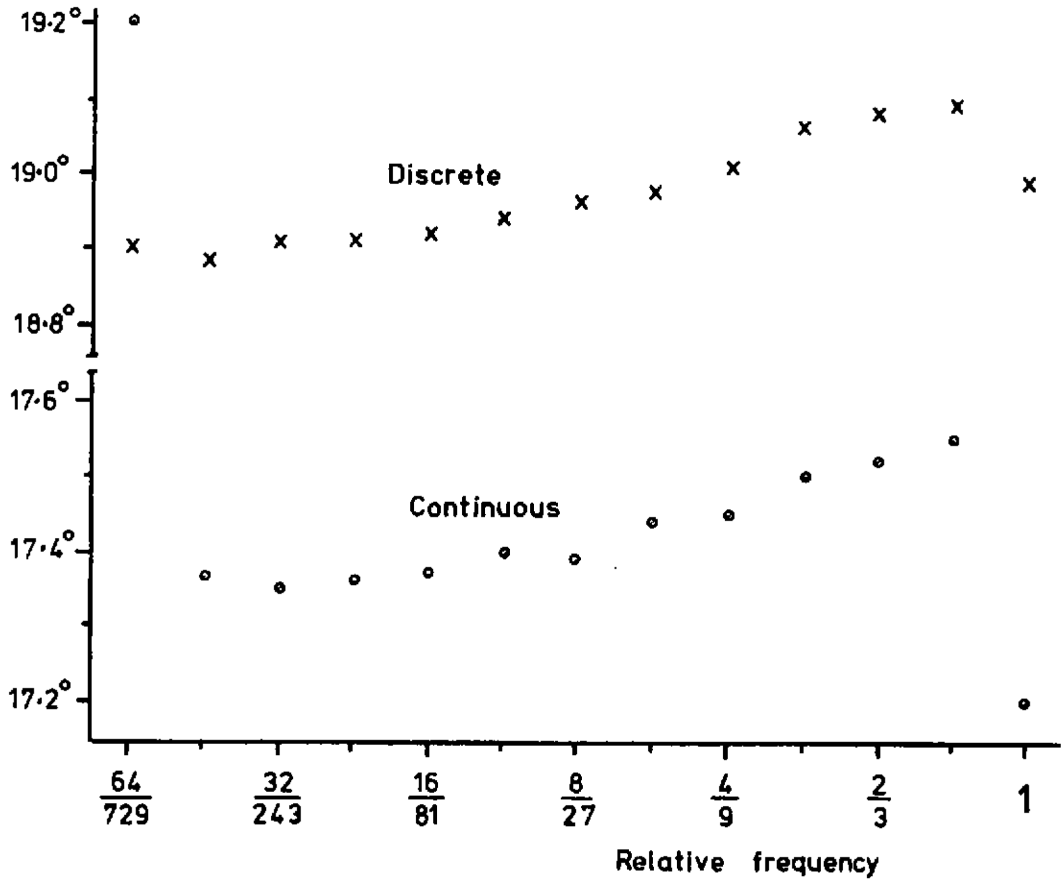

Fig. 1 Theoretical beamwidth

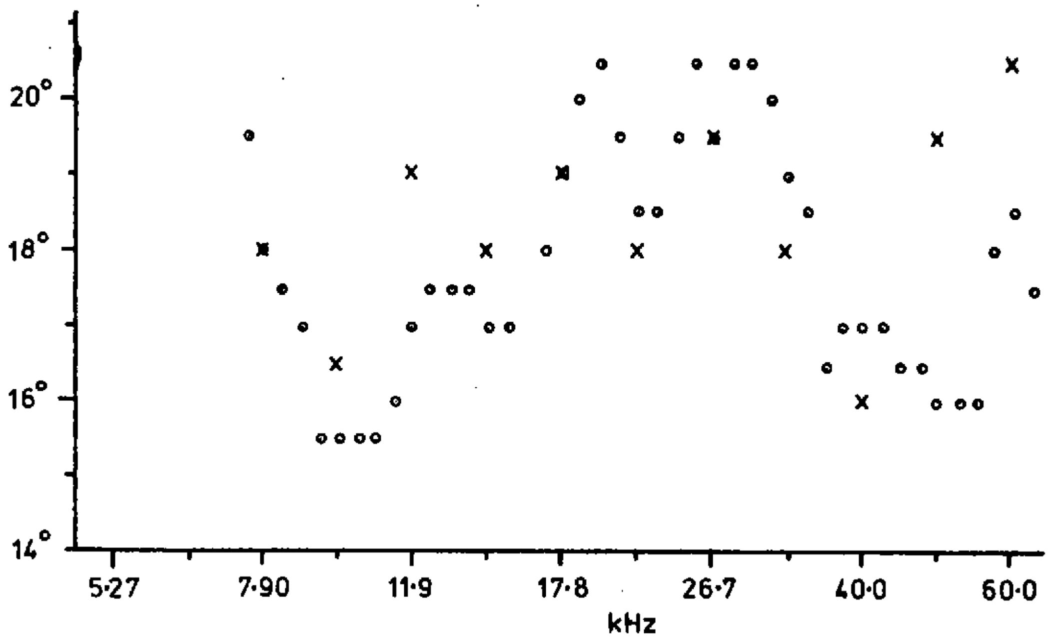

Fig. 3 Measured beamwidth

× Discrete ∘ Continuous

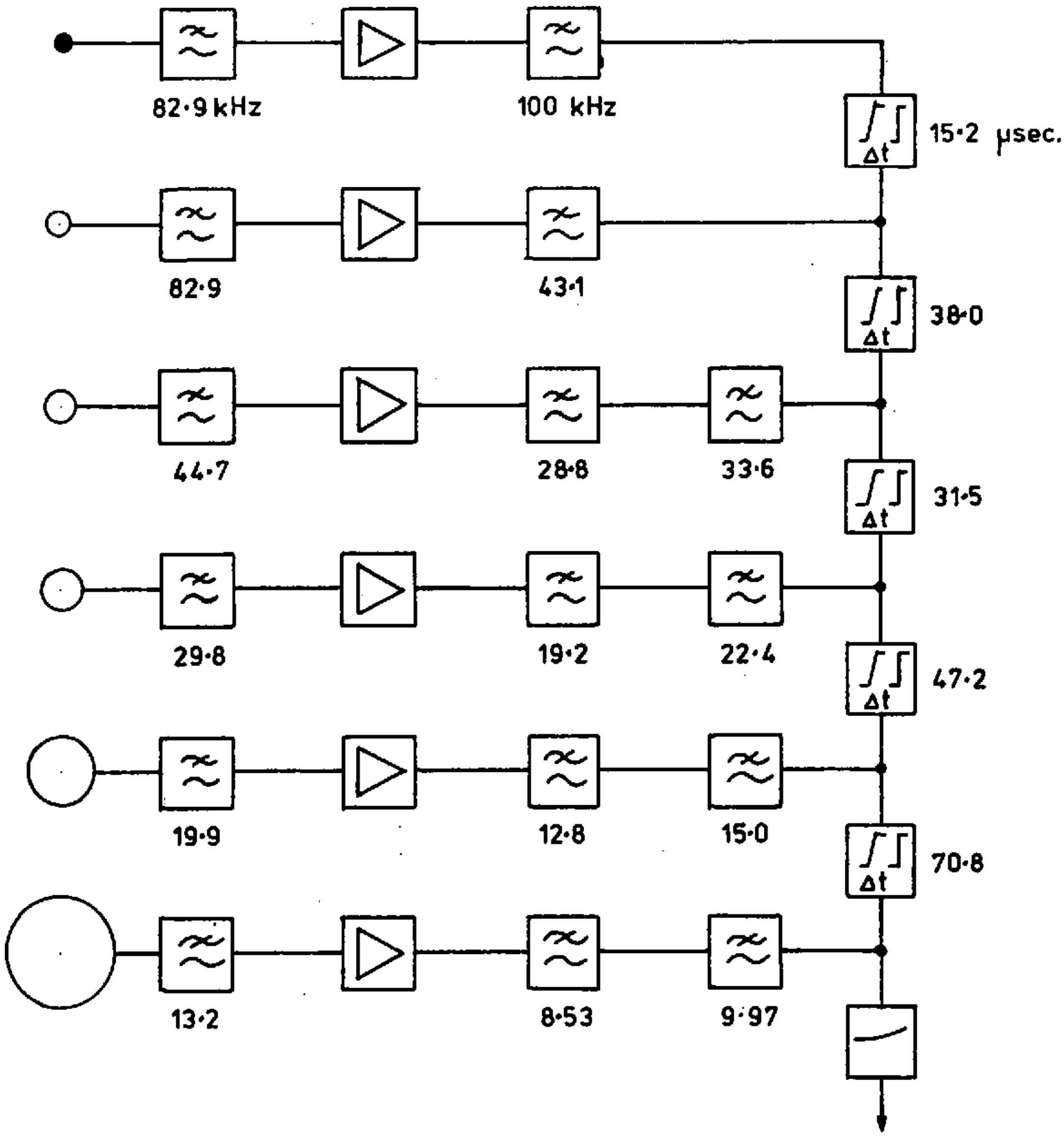

Fig. 2 Block schematic of equalising system for 8:1 frequency range