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A PHASE STEERED PARAMETRIC ARRAY FOR SUB-BOTTOM PROFILING

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INTRODUCTION

As part of the Marine Science and Technology (MAST 2) research effort the Commission of the European Communities funds a programme whose goal is to define the parameters of new remotely operated devices for characterisation of the seabed and the sub-bottom structure. The possible applications of this technology are numerous, ranging from the geology to off-shore engineering and propagation modelling, from investigations of sediments for pipe and cable routes to the detection of sub-bottom objects and assessing dredging efficiency and ability. This programme is known under the acronym REBECCA - REflection from Bottom, Echo Classification and Characterisation of Acoustic propagation.

In order to establish a correlation between the geotechnical and geophysical characteristics of the seabed and their acoustic properties, as determined by remote acoustic sensors, it is necessary to measure the sediment parameters by a number of independent methods. The geotechnical parameter estimation for example is undertaken by tests on core samples in the laboratory or by in-situ measurements at sea and the geophysical parameter estimation is made from reflection or refraction seismic surveys. Acoustic parameter estimation such as back/forward scattering can be made by remote sensing using acoustical techniques.

REBECCA involves contributions from four members of the European Community, Greece, France, Denmark and the United Kingdom with seven different participating establishments. Each establishment provides its own particular expertise to the programme to develop an integrated European research effort to the overall problem. The remote acoustic sensing of the seabed will be undertaken by two systems based on non-linear sonars (parametric arrays). The first equipment has been developed at the Department of Industrial Acoustics in the Technical University of Denmark (TUD). Operating at secondary frequencies of around 16 kHz, this unsteered single beam system will be used in the echosounder mode at near normal incidence to measure direct returns from the seabed and provide a delineation of the sub-bottom structure to a depth of about 1 metre. In order to provide for lower frequency measurements and a greater penetration capability a second non-linear sonar has been developed at Loughborough University of

Technology (LUT). It is this latter sonar that is the subject of this paper.

THE PARAMETRIC SONAR

The parametric sonar utilises the very small non-linearity of the process of sound wave propagation in water to generate additional frequency components in a sound beam transmitted from a transducer driven at two *primary* frequencies F_1 and F_2 near the transducer resonance. This forms a dual frequency sonar beam, designated the primary beam, with F_0 the average frequency of F_1 and F_2 generally fixed at the centre frequency of the system bandwidth. This form of operation is normally termed the Double Side Band Suppressed Carrier (DSBSC) mode of operation. Alternatively a similar system can be operated by the amplitude modulation of a single carrier frequency signal to provide the Amplitude Modulated (AM) mode of operation.

As the sound propagates, new frequencies are formed effectively by the interaction of sound with sound, along the length of the primary beam. The lowest of these frequencies is the difference frequency $F_d = F_1 - F_2$, and the primary beam then acts as an end-fire array of sources at the difference frequency. The effective length of this array, the *virtual array*, is determined by the attenuation of the primary frequency waves which occurs at low powers as a result of absorption. At higher powers additional non-linear losses occur due to the generation of other intermodulation products, (such as the sum frequency) and harmonics of the primary waves. The length of the virtual array is approximately given by the term $(2\alpha)^{-1}$ (for low transmitted levels) where α is the small signal attenuation coefficient in nepers/m. For low primary frequencies of around 20 kHz therefore the virtual array length is about 1500 m, at 40 kHz about 400 m, and at 80 kHz about 100-150m.

This type of parametric sonar provides a number of advantages over its linear counterpart, but at the cost of a very low conversion efficiency and some complexity in design. Typical conversion efficiency is of the order of 1%, which depends directly on the ratio of F_0/F_d , the step-down ratio. The greater the step-down ratio the lower is the system efficiency. This means that the

Source Level SL_d at the difference frequency will be some 40 dB less than the Source Levels SL_1 and SL_2 at the two primary frequencies (normally considered equal) for a typical step-down ratio of about 10.

For the present requirement, which aims at high precision in seabed delineation in terms of area, the non-linear sonar provides a narrow beam at low frequencies, with a beamwidth similar to that of each high frequency beam. The linear dimensions of the parametric array required are also reduced in the ratio of F_0/F_d . For a step down-ratio of 10, therefore, the active surface area of the array need be only 1/100th of that of its linear counterpart to produce the same beamwidth. This advantage is obviously of primary consideration in terms of expense, size, weight and handleability of the equipment at sea. In the present case, it means that the array can be conveniently installed in a towed body. A further advantage inherent with this type of system is that the resultant low frequency beam pattern is virtually free of side lobe structure. The resultant beam, however, is not 'perfect' as there are 'skirts' to the main lobe, but the energy contained in these is much reduced compared to that of the conventional side lobe pattern. An additional advantage for the present application is that this form of sonar preserves at F_d the bandwidth available with the high frequency array. Thus very short CW pulses can be transmitted at F_d or alternatively the bandwidth can be used for FM pulses and subsequent correlation detection.

The overall parametric system produces a multi-frequency capability, providing signals not only at the carrier frequencies F_1 and F_2 at very high levels, but also at F_d and at the sum frequency $F_1 + F_2$ together with harmonic frequencies and other intermodulation frequency products. In some circumstances this multi-frequency capability can be employed to advantage.

SONAR SPECIFICATION AND DESIGN

LUT has had considerable experience in the design of non-linear sonars and has developed beam steered systems working at carrier frequencies of both 20 kHz and 40 kHz [1]. However for this particular requirement the sonar is required to operate in water depths of 150 m or less and this places some limits on the operational carrier frequencies as determined by the length of the virtual array.

Operation within the virtual array length involves some loss in the effective Source Level SL_d as the source is truncated before it is fully developed; this factor also involves some broadening of the beamwidth. As the non-linear parameters of the seabed sediments are different from those of the sea itself, generation of the difference frequency within the sediment will take

place at a different rate from that within the body of the sea, a factor that may not be desirable. Finally if the sonar is used at very short ranges there is always the possibility of secondary regeneration. A high Target Strength target could reflect enough energy at the carrier frequency to provide secondary regeneration on the return trip and thus produce an erroneous echo level.

For these reasons it was desirable to design a system with a virtual array length reasonably matched to, or shorter than, the operational depth: as previously noted this requires carrier frequencies of no less than approximately 80 kHz. For accurate delineation of the sea bed it is necessary to operate with as narrow a beam as possible commensurate with transducer size. A transducer array of size $20\lambda \times 20\lambda$ has a -3 dB beamwidth of about $3^\circ \times 3^\circ$, which at 100 m range would insonify some 25 m^2 of the seabed, a resolution in area that is considered acceptable. With a wavelength of the order of 2 cm at 75 kHz this results in an array with a surface area of $40 \text{ cm} \times 40 \text{ cm}$ which provides a system that is reasonable in both size and weight.

Whilst a narrow beamwidth is essential for the research envisaged, under operational conditions at sea it presents a major stabilisation problem. Mechanical stabilisation was considered uneconomic and hence a compromise has been made by towing the system in a relatively stable body and electrically steering the array in one plane only. This steering will probably be used to compensate for the pitch in the towed body.

For primary frequencies around 80 kHz, used to generate a secondary frequency of 5 kHz, the step down-ratio is 16. To obtain Source Levels in the region of 190-200 dB re $1 \mu\text{Pa}$ at 1m requires SL_1 and SL_2 to be approaching a level of 240 dB re $1 \mu\text{Pa}$ at 1m. This produces two more problems; the first is the possible onset of cavitation and the second is that the system now approaches saturation limits.

Cavitation is less of a problem around 80 kHz than it is at lower frequencies and even at very shallow depths it is probable that the transducer array could sustain a power density of more than 10 W/cm^2 without cavitation. With an array surface area of about 1600 cm^2 , the array should therefore be capable of handling some 16kW (acoustic) at its surface.

As the Source Levels at the primary frequencies increase, the array is no longer limited by small signal absorption and approaches saturation. The critical Source Level is usually defined in terms of SL_0^* which is the rms Source Level which corresponds to shock formation at the Rayleigh distance, which for sea water is given as 281 dB re $1 \mu\text{Pa}$ at 1m/kHz [2]. The critical level for $SL_1 = SL_2$ becomes therefore:

$SL_1^* = 281 - 20 \log F_0$
 At 80 kHz this would give $SL_1^* \approx 243$ dB re 1 μ Pa at 1m. For SL_1 greater than this the system would be severely saturation-limited and in general it would be preferable to work at levels at least 5 dB less than this, i.e. $SL_1 = SL_2 < 238$ dB re 1 μ Pa at 1m.

THE TRANSDUCER ARRAY

A transducer array for this type of operation is a relatively expensive item (£20k-£30k). Fortunately, one with very similar characteristics to those required was located at the Deacon Laboratory of the Institute of Oceanographic Sciences. This consisted of a titanium plate with 729 integral individual elements, resonant at approximately 75 kHz and arranged in a matrix of 27×27 with approximately 0.75λ spacing. This provided an array of $20\lambda \times 20\lambda$ with a resultant beamwidth of $3^\circ \times 3^\circ$, which was identical to the system requirement. Bandwidth was approximately 6 kHz. Each stave was wired separately in parallel, and the 27 staves finally connected together to form a single parallel-wired sonar array. To reconfigure this as an individually staved system to permit beam steering was therefore a relatively straight forward modification and undertaken by the Deacon Laboratory to LUT specification. The rewired transducer then provided 13 individual staves each of 54 elements in parallel whilst a single stave of 27 elements was retained as a 'hydrophone'. The transmitting elements now drive an effective area of $20\lambda \times 19.5\lambda$, 0.156 m^2 ; however, the active heads of the piston elements comprise a surface area of 0.108 m^2 . This area is sufficient to avoid cavitation restrictions to a maximum loading of 10 W/cm² or up to acoustic powers of above 10 kW. The Directivity Index of the array is approximately 35 dB and thus at 10 kW (acoustic) the maximum Source Level SL_0 for a single carrier frequency could be as high as 246 dB re 1 μ Pa at 1m. Each individual stave is driven by a separate ultra-linear MOSFET power amplifier module rated at 1 kW and thus with the rated electrical-to-acoustic efficiency of 80%, the drive system of 13 kW has a power rating virtually identical with the cavitation limit for a single primary frequency. However the array elements themselves have a specification voltage limitation of 600 V pk/pk, reducing the power per stave to 535 W, i.e. a total electrical power of 6,955 W, or a total acoustic power of 5,564 W. For the two-frequency system where the power is equally divided between the two tones, each maximum $SL_1 = SL_2$ would be reduced to about 240.5 dB re 1 μ Pa at 1m.

The above levels for SL_1 and SL_2 can only be achieved for very small values of F_d , i.e. operation close to the resonance frequency. As F_d is increased the maximum values obtainable for SL_1 and SL_2 are

reduced by the bandwidth limitations of the array. This in its turn leads to reduced levels for SL_d but within the bandwidth of the array this effect is more than compensated for by the increasingly efficient generation of F_d as a result of the reduced step-down ratio.

Fig.1 NLA System Block Diagram

These bandwidth limitations also account for the use of the DSBSC form of operation as opposed to the possibly more convenient AM mode which is slightly more efficient in terms of power conversion and does not demand highly linear amplifiers. For a given F_d , AM demands twice the bandwidth (covering $F_0 \pm F_d$) of the DSBSC mode, and the present transducer is rather bandwidth limited. As the two primary waves form 'beats' (a linear process) when they are added together, and the amplitude of these beats is twice that of a single primary wave, the peak power required will be four times higher. If the power amplifier is peak power limited the levels of SL_1 and SL_2 may have to be reduced. In considering the cavitation limits involved the system should also be operated within the requisite peak power levels.

TRANSMISSION SYSTEM

The transmission system, Figure 1, includes of a multi-channel 16-bit resolution D/A interface. The system allows for the generation of 16 channels of parallel data during a 32 ms time window. Computations of the required channel waveforms to permit phase steering

of the array are generated by a host PC (486DX2, 66 MHz) using routines written in Borland Pascal version 7. These are assigned to memory buffers located in the transmission module outside the computer. The PC contains an interface card incorporating the firmware logic (in ASICs) for communicating with and controlling the transmission buffer module during data write and transmit (parallel) read conditions. The card accepts software commands to define each transmission and the card then operates under local crystal control once triggered, leaving the PC host free to acquire echo data through a companion receiver system. The external transmit module comprises 16 memory blocks of 32 k words (32 k x 16 bits). These are sequentially loaded with waveform data from the PC with each buffer block in turn appearing temporarily overlaid on a section of main computer memory. During transmission 13 buffers are addressed together from the local address generator and their contents are clocked simultaneously into D/A converters from which the 13 analogue drive signals, after filtering, pass to the transducer stage power amplifiers.

RECEIVER SYSTEM

During the first sea trials a matching multichannel digital receiving system was employed to capture simultaneous echo data from several hydrophone inputs. The maximum capture window of 16 ms (chosen for sub-bottom echo capture) limited its versatility during the initial performance tests and for much of the time only single channel data was captured. The host PC was able to process the received channel data on-line and provided an 'A' scan and power spectrogram updated by each transmission. This display facilitated direct measurement of the array beam pattern as the array was mechanically steered and the signal received on the appropriate far field hydrophone.

TRIALS ARRANGEMENTS AND SITE

The first series of trials with the new equipment was undertaken at Loch Duich in Scotland during June 1993. This trial site is operated by the Scottish Office, Agriculture and Fisheries Department (SOAFD) who generously made the site available to LUT and provided some base support in association with another SOAFD/LUT project. In addition to the essential base facilities the site is equipped with a small floating laboratory operating in over 90m of water. This raft is fitted with a mounting system that held the transducer array in the vertical echosounding mode, and provided a tilt movement in two mutually perpendicular axes of $\pm 20^\circ$. These movements were resolvable to an

accuracy of 0.01° and the control instrumentation was available both on the raft and ashore.

The two receive transducers used were single wideband ball hydrophones. One was mounted 16 m below the array, suspended from the training gear frame which itself was operated at a depth of 9 m below the surface. The second was suspended at a range of 72m and relatively close to the sea bed. At short ranges the hydrophones were rigged in a relatively stable configuration by a three point suspension. The deep hydrophone, however, although weighted, was subject to relative movement between the transducer array and the hydrophone itself. With the narrow beams involved this produced considerable experimental problems in anything but calm conditions.

ARRAY PERFORMANCE

The near field of the transducer at 75 kHz extends out to approximately 8 m and hence the closest hydrophone could be used for all carrier frequency measurements. The only adjustments made were to set the output levels of each power amplifier to ensure that for equal input powers, each stave contributed an equal pressure level at the monitoring hydrophone at the centre frequency of operation. At F_0 this could be achieved with a high degree of precision but this could not be completely preserved over the full bandwidth of the transducer due to slight variations in the sensitivity of the transducer elements. Equalisation was still better than 0.5 dB over all frequencies.

After equalisation the beampatterns of the array were measured at a number of frequencies in both the scanned and unscanned axis. Figure 2 shows a typical plot of the beam pattern of the array at 75 kHz, taken in the scanned plane. Slight asymmetry is apparent at the first sidelobe, but in general the pattern can be considered reasonably satisfactory, with a measured -3 dB beam width of 2.75° .

Fig.2 75 kHz Beam Pattern

Fig.3 Transducer Frequency Response.

The Source Levels obtained from the power amplifier/transducer system for a single frequency carrier throughout the usable bandwidth are shown in Figure 3. The -3 dB bandwidth is approximately 6 kHz. The maximum Source Level SL_0 was measured to be 241 dB re 1 μ Pa at 1m. This compares with the level of 243.5 dB re 1 μ Pa at 1m previously predicted on the basis of the assumed efficiency of 80%. Each of the two individual Source Levels, SL_1 and SL_2 is 3 dB less than the figures shown in Figure 3. For operation with $F_d = 2$ kHz therefore $SL_2 = 238.8$ dB re 1 μ Pa at 1m and SL_1 should be identical. For $F_d = 7$ kHz however, SL_1 and SL_2 are 233 dB and 235 dB re 1 μ Pa at 1m, giving an average loss of about 4 dB to each carrier. This provides an 8 dB loss to SL_d due to the limited transducer bandwidth. The system provides for 13 resolvable beams within the phase steerable sector, each of about 3° width; hence the scanned sector is about $\pm 20^\circ$. In order to check the correct operation of the beam steering the thirteen staves of the array were driven with a series of frequencies ranging from 74.4 kHz (stave 1) to 75.6 kHz (stave 13); these frequencies were chosen so that the centre stave was driven at 75 kHz. Each stave's transmission was phase coherent at the instant when the projected beam crossed the zero axis of the array.

Fig.4(a) Scanned Pattern at 0° .

The result was a beam scanning the 40° sector every 10 ms, i.e. derived from the 100 Hz difference frequency between each stave. A hydrophone sited on the array's transmission axis therefore receives, during a single scan period, the pressure changes associated with the complete transmission pattern of the array, as shown in Figure 4(a). The array was then mechanically steered through 10° so that the hydrophone was 10° off-axis. The slight array asymmetry measured by direct beam plotting is also apparent at 0° steer but not at 10° steer as shown in Figure 4(b). The apparent reversal of the first side lobe asymmetry in Figure 4(a) with respect to Figure 2 is due to the direction of scan not being specified for this test.

Fig.4(b) Scanned Pattern at 10° .

NON-LINEAR SONAR PERFORMANCE

Measurements made at the difference frequencies were all taken on the longer range hydrophone. The range was considered near enough to the end of the virtual array for 'far-field' conditions to apply for F_d . Figure 5 shows the beam pattern for the NLA sonar at $F_d = 5$ kHz, and clearly illustrates the lack of sidelobe structure over the angular range $\pm 15^\circ$ [Sidelobe structure in an NLA sonar only normally occurs at low step down ratios when the transducer array size is significant in terms of wavelength at F_d]. The measured -3 dB beamwidth is about 2.5° , which compares favourably with the beamwidth measured at 75 kHz. Source Levels at the difference frequencies were measured over the range 2 kHz - 7 kHz.

At 72 m range the effective SL_d should be within less than 1 dB of that obtained at infinite range. In Figure 6 the measured values of F_d are plotted as a function of $SL_1 \approx SL_2$, together with the predicted values for F_d . As will be noted the theoretically predicted curves deviate from linearity at a value of $SL_1 = SL_2$ of about 233 dB re 1 μ Pa at 1m as saturation approaches. Up to this Source Level a 5 dB increase in both SL_1 and SL_2 results in a 10 dB increase in SL_d . The measured

levels at best are within 1 dB of the predicted levels and at worst within 3 dB of the predictions.

Fig.5 5 kHz NLA PATTERN

Fig.6 Measured and Theoretical Primary and Secondary Source Levels

CONCLUSIONS

The non-linear sonar developed at LUT now meets the specifications of the REBECCA programme [3]. At 5 kHz it gives a Source Level of approximately 196 dB re 1 μ Pa at 1m and a beam of approximately $2.5^\circ \times 2.5^\circ$. A -3 dB bandwidth of ± 3 kHz should be available at 5 kHz, permitting pulses as short as 200 μ s to be transmitted. The phase steering characteristics also appear satisfactory over a $\pm 20^\circ$ sector. This steering capability will be further developed to ensure that the selected NLA beam incidence angle to the seabed remains constant. Sensed towfish attitude errors should therefore be dynamically correctable on one axis.

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REFERENCES

1. Cook, J.C., Goodson, A.D. and Griffiths, J.W.R. 1992 'Experiences with a versatile NLA sonar system', Proc. IoA Non Linear Tutorial Meeting, University of Bath, 8th July. 14(3) p27-52 1992.
2. Merklinger, H.M., Mellen, R.H. and Moffat, M.B. 'Finite amplitude losses in spherical sound waves', *J.Acoust.Soc.Am.* 59 p755-759 1976.
3. Woodward, B., Goodson, A.D., Cook, J.C., and Lepper, P.A.. 'Developments in Non-linear Acoustic Methods, Preliminary results of open water trials of a parametric array'. in: J-P.Sessarego and M.E.Zakharia (eds), 'REBECCA Progress Report - EC Contract MAST2-CT91-0002, October 1993.