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LOCALISATION OF SOUND SOURCES WITH SEA-BED GEOPHONES

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ABSTRACT

Geophone sensors on the sea-bed offer a mechanism for detecting and localising noise sources in the ocean. Recent work is described in which an array of deployable sensor units for use in shallow water environments was designed, produced and tested. The objective was to design a sensor unit with acceptable coupling performance with the sea-bed, while maintaining deployability and constraining costs. Data from a sea-experiment showing the coupling performance achieved and the ability of the sensors to localise acoustic sources in the water are presented. The potential of an array of sensors to provide enhanced directional discrimination is explained.

1. INTRODUCTION

The requirement to determine the location of a sound source in the ocean frequently arises in underwater acoustics. The deployment of a sensor system with significantly larger response to energy arriving from a particular direction, which can be varied, allows the bearing of a source to be determined. In addition, such a system increases the signal to noise ratio, and hence, at low signal to noise ratios, the detectability of the source. Traditionally in sonar applications, arrays of hydrophones have been used to achieve the directional response. Arrays deployed to different locations can then determine the location of a source by triangulation methods.

The aperture of a hydrophone array required to achieve a certain directional response is proportional to the wavelength of the sound to be detected. Low frequency arrays need to have a large aperture and are for convenience of deployment usually line arrays, either towed from a vessel or deployed on the sea-bed. Arrays for higher frequencies need not be as large and can frequently be mounted on the hull of a submarine or surface vessel. Planar and other configurations are then possible and the hydrophones are usually mounted in front of baffles which improve the directional response.

The need for arrays with high directionality at low frequencies has led to consideration of the use of directional sensors in sonar applications. Hydrophones are sensitive to the pressure in a sound wave which is a scalar quantity. Associated with the pressure are the acoustic velocities of the medium. Sensors such as geophones and accelerometers respond to the velocity of the medium which is a vector quantity and therefore these sensors have a directionality of their own.

Because the underwater medium is inhomogeneous with significant variations of sound speed with depth, sound is refracted in the vertical plane. Propagation paths in which energy interacts repeatedly with the sea-bed are often encountered. At low frequencies a substantial proportion of the energy is transmitted through the sea-bed itself, even when the source and receiver are located in the water. A difficulty encountered using a geophone to detect acoustic velocities in water is ensuring a reasonable output from the sensor relative to vibrational noise. One solution is to place geophones on the sea-bed where they respond to motions of the sea-bed set up by the acoustic field in the water. However, a number of problems remain. Firstly achieving good coupling between the sensor and the sea-bed is still not straightforward, and secondly the wave-field in the sea-bed is more complex than in the water consisting of waves of a number of different types including high speed compressional waves and low speed shear and interface waves. These factors mean that the performance that can be obtained from arrays of sea-bed geophone sensors is difficult to predict.

This paper describes work in which a design of a geophone sensor unit that can be deployed in shallow water environments was developed. A recent sea experiment in which a number of the sensors have been deployed is described. Data showing the coupling performance of the sensors and the ability of the sensors to localise acoustic sources in the water are presented. Predictions of the beamforming performance that can be obtained from an array of sensors are presented.

2. DESIGN OF THE GEOPHONE SENSOR UNIT

The objective was to produce a design of a sensor unit that could be deployed conveniently from a surface vessel onto the sea-bed in shallow water. The sensor should be suitable for incorporating in an array of similar sensors. Costs should be minimised subject of course to the requirement that the sensor must have the ability to obtain useful data. The sensor should measure accurately the three components of motion of the sea-bed, i.e. produce an output which is proportional to the motion of the sea-bed that would exist if the sensor were not there. Three components are required so that direction of arrival information can be obtained from measurements of sea-bed velocities, and the type of waves arriving at the receiver can be determined from the locus of sea-bed velocity in the vertical plane.

Marine seismologists have used ocean bottom seismometers (OBS) for many years to measure seismic noise. The frequencies of interest are generally lower than those of interest here, and the water depths are generally much greater. Difficulties have been experienced obtaining accurate measurements of the horizontal components of sea-bed motion due to resonances in the response of the sensors used. This is due to the relatively large mass of most OBSs and the relatively low stiffness of sediments, particularly in deep water. Strings of geophones have used in the seismic industry in ocean bottom cables and here usually few precautions are taken to ensure an uniform and reproducible response from the geophones. A substantial proportion frequently fail to produce any useful output because they do not reach the sea-bed in the correct attitude or they land on uneven sections of the sea-bed and are then susceptible to noise caused by currents.

A recent paper by Duennebier and Sutton [1] has reviewed the reasons for poor coupling in OBS and presented recommendations for achieving good performance. This extended previous theoretical modelling [2] to include horizontal motions and horizontal response but the earlier reference also contains recommendations which are relevant. These authors point out that the only reliable method of achieving good coupling for both vertical and horizontal components is to make the sensor neutrally buoyant and bury it in the sediment. While technology exists in the off-shore services industry to perform this, it is very expensive and impractical for this application. The recommendations for a high-fidelity on-the-sea-bed sensor have been followed here to produce a design for this application.

The vertical component of particle velocity is continuous across the sea-bed/water interface. The horizontal component is not continuous and a sensor placed on the sea-bed is therefore subject to different forces from motion of the sea-bed and the water. The response of the sensor has a resonance frequency determined by the effective mass of the instrument, the added mass of water displaced when the package is set into motion, and the stiffness of the sediment. These are different for vertical and horizontal components of motion. The transfer function between sensor motion and sea-bed motion approaches unity below this resonance. The transfer function between sensor motion and water motion approaches unity above this resonance. For a sea-bed motion sensor the resonance frequencies should therefore be made as high as possible. For horizontal motion this is achieved by minimising the mass and added mass of the package. For vertical motion the resonance frequency is not usually so much of a problem and can be made large by adopting a variety of approaches.

The forces applied to a package can set up a tilting motion which, depending on the position of the sensors relative to the axis of rotation, can result in an erroneous output on the vertical component. These effects are minimised if the footprint of the package is large and the vertical cross section presented to horizontal motion of the water is small. However, the response to high frequency shear and interface waves decreases if the package size approaches a significant fraction of a wavelength. To minimise the effect of tilting motion generated by vertical excitation, the package should be symmetrical about the vertical axis and the sensors should be close to the axis. Placing the package in a low profile particulate bag has been demonstrated to reduce noise from currents in packages deployed on hard bottoms, although this is obviously is likely to reduce the frequencies of coupling resonances.

The design adopted was therefore as follows. The geophones used were Mark Products L15B 4.5Hz Gal'perin geophones. They were mounted on a two-axis gimbal in a Gal'perin configuration, a compact configuration in which each sensor of the orthogonal set is at an equal angle to the vertical (54.7°). The geophone axes pass through the axes of the gimbal so the geophones are insensitive to rotations about these axes but they may be sensitive to tilting of the whole package because the axis of this motion may be at a different height. The geophones were contained in a aluminium case. A Benthos AQ-4 hydrophone was mounted on the top of the case. A quantity of silicon oil was used to prevent motion of the gimbal at the frequencies of interest (above 1Hz) but allow it to move to accommodate the package coming to rest at an angle. The case was fixed to a circular polypropylene plate beneath which were a system of gravel bags surrounding the lower half of the geophone case. The gravel bags were to improve the area of contact on hard sea-beds. On top of the plate was a convex free-flooding cover to provide a smooth upper surface over which water could flow. The unit was designed to be lowered on a bucket handle which was sprung so that it retracted down to the plane of the plate when the unit reached the bottom. The total weight of the package was about 60kg, the radius 0.3m, and the height 0.15m. A drawing of the sensor unit is shown in Fig. 1.

3. SEA EXPERIMENT

An array of 14 of the sensor units was deployed in a recent sea-experiment. The experiment was conducted at a location near the edge of a continental shelf in about 100m of water. The sea-bed was relatively hard consisting of a mixture of sand and gravel. The units were deployed in a V-shaped array configuration with a nominal element spacing of 10m. The units were lowered from the research ship at the desired positions but the final positions on the sea-bed were somewhat different due to variable currents during the deployment period. The sensor outputs were amplified in the geophone cases and digitised at a sampling frequency of 488Hz and to 24bit resolution. The signals were passed by individual wires to a central unit where the data was multiplexed and sent to an RF link on a surface buoy for transmission to the research ship. An additional sensor unit with an internal shaker was deployed to make measurements of the coupling performance of the units on this sea-bed.

Measurements of the response of the array to ambient noise and shipping contacts in the vicinity were taken. Measurements of the response of the array to transmissions from acoustic projectors lowered from the research ship were taken to provide information to determine the position and orientation of the sensors. Measurements were also taken of the response of the array to the excitation of the sea-bed by the dropping of a weight on the sea-bed at moderate distances from the array. Analysis of this data is still underway and is not reported here. Measurements of the coupling performance of the sensor units and the response of a sensor unit to acoustic transmissions at various frequencies to show the ability of the sensors to determine the bearing of sources of sound have been analysed, and are presented here.

4. COUPLING PERFORMANCE

Techniques involving the use of internal shakers for assessing the coupling performance of OBSs have been used for some time by several groups [1], [3] and [4]. The internal shakers used are miniature electric motors with eccentric weights which can be driven at frequencies in the range of interest. The response of the sensor package to the shaker is identical to the response to water motion if the motor is located at the effective point of application of the force applied by the water motion (and the sea-bed is not moving). If coupling between a sensor and the sea-bed is good, the velocity response of the sensors should have a positive slope of 18dB/octave. If the slope is less than this it usually indicates significant tilting and coupling resonance frequencies in and below the frequency range considered.

Measurements were taken on the single sensor unit deployed from the research ship. Ideally, the unit should have been allowed to settle for a period of time as improvements in coupling performance have often been observed after an OBS has been allowed to settle. However, the ability of the research ship to keep station even with the aid of anchors was limited and this meant that the unit could not be left undisturbed for any significant period of time. The estimate of coupling performance is therefore likely to be pessimistic as some improvement is likely in extended deployments.

The velocity response output is shown in Fig. 2. The results have been corrected for the fall-off of the nominal response of the geophones below their resonant frequency (4.5Hz). It is evident that the response increases at about 18dB/octave up to a frequency of 22Hz for the horizontal component and 28Hz for the vertical, indicating good coupling in these frequency ranges. The velocity response of the horizontal component is as expected larger than the vertical showing that the sediment stiffness is lower in this direction.

5. LOCALISATION OF SOUND SOURCES

Measurements of the output of the single unit to a number of narrowband lines transmitted by an acoustic projector were measured. The locus of the measured velocity in the horizontal plane is plotted in Fig. 3 for a tone at 11Hz and a tone at 72Hz. The lower frequency is one where coupling to the sea-bed is good, and the higher where coupling to acoustic motions in the water is good. In the high frequency case, the direction of the source is indicated clearly by the direction of motion but in the lower frequency case the locus is not as convincing and the estimate of direction differs from the obtained with the high frequency data.

At the higher frequency sound is propagated through the water column whereas at the lower frequency propagation through the water is more difficult as there are no propagating modes. Sound is transmitted through the water by other mechanisms (diffraction and tunnelling) and through the sea-bed. The poorly defined direction of arrival as measured on the geophone unit may be a consequence of less than perfect coupling as has been observed in more extreme cases in other experiments [5], inferior signal to noise ratio, or scattering due to lateral variability in the sea-bed. The data from the array is being analysed to provide more information on this aspect.

The sensor units were not provided with an independent means (such as an on-board compass) for determining their orientation. Acoustic transmissions from known directions are therefore required to provide this information. Examination of the locus alone will only determine the orientation to within an multiple of 180° because particle motion in a certain vector in the horizontal plane could result from sound arriving from both directions. However, in instances where the energy arriving is an acoustic wave over some of the frequency range, it has been found that examination of the relative phase of the pressure and the velocity will resolve this indeterminacy. Once the orientation of the sensor unit has been found, the direction of other sound sources can be determined.

5. BEAMFORMING

The above procedure for determining the bearing of sound sources using the directivity of a single geophone unit is effective at high signal to noise ratios. For low signal to noise ratios, it would not be effective because the locus would not provide a clear estimate of direction of particle motion due to noise received from other directions in the relatively broad beampattern of the sensor. To estimate the bearing of weak sources, a system with greater directionality is needed. The use of an array of sensors is required and directional sensors have an important contribution to make here too.

The outputs of the geophones can be beamformed in the following way. The horizontal component of velocity in the direction of steer is calculated, phase or time delays applied according to the position of the element and the wavenumber of the field being examined, and the different elements summed. With conventional beamforming, the beampattern will have a null in the direction perpendicular to the steer direction superposed on the beampattern that would be expected from an equivalent array of hydrophone sensors.

An example of the performance expected of an array of geophone sensor units in the configuration used in the sea experiment is shown in Fig. 4. The V-shaped array configuration was used in the sea experiment to avoid the ambiguity between wavenumber and arrival angle that would exist with a line array. Plotted is the response of the array to an incident plane wave arriving horizontally from a bearing of 90° with a wave speed of 1500m/s, for various steer angles. The performance the horizontal geophones and the hydrophones in the array are presented for comparison.

The design frequency of each line segment of the array would be 75Hz if it was considered in isolation. The plot shows that there are no aliases or high side lobes in the beampattern of the V-shaped array configuration until the design frequency of the line segments is approached. The performance of the geophones is considerably better than the hydrophones in this example because the directional response of the sensors cuts out the signals which would otherwise be received through the side lobes of the array for steer angles of 180° and 360°. Adaptive beamforming techniques offer the possibility of further improvements to the performance obtainable with conventional methods, and of adapting the shading of the array to the noise environment at a specific location.

6. CONCLUSIONS

A geophone sensor unit suitable for deployment in shallow water environments has been developed. The sensors have been tested during a recent sea experiment. Coupling performance achieved on the hard sea-bed at the location of the experiment was measured and was found to be adequate for this application. However, better performance would be desirable and on less hard bottoms would probably be essential. A number of ideas for improving coupling performance are currently being investigated.

The direction of sound sources has been successfully determined from inspection of the locus of the measured sea-bed velocity in the horizontal plane. The accuracy of this technique is very good at higher frequencies where most of the energy is arriving as an acoustic wave in the water and the sensor is sensitive to motion of the water. The location of sound sources can be deduced from bearing information from several sensors by triangulation methods. The accuracy of the estimate of direction at low frequencies where more of the energy is arriving in the sea-bed and the sensor is sensitive to sea-bed motion is poor. Further work needs to be done to determine whether this is a problem with the sensor coupling or a fundamental problem imposed by the propagation and noise environment.

For the estimation of the bearing of weak sources, an array of sensors providing a higher directionality is required. Predictions of the performance of an array of geophone sensors presented here indicate that the directionality of the individual sensors can be combined with that of the array to produce superior performance to an equivalent array of omnidirectional hydrophones.

7. REFERENCES

[1] F K Duennebier and G H Sutton, Fidelity of ocean bottom seismic observations, Marine Geophysical Researches, 17, pp535-555 (1995).

[2] G H Sutton and F K Duennebier, Optimum design of ocean bottom seismometers, Marine Geophysical Researches, 9, pp47-65 (1987).

[3] A M Sauter and L M Dorman, Instrument calibration of ocean bottom seismographs, Marine Geophysical Researches, 8, pp265-275 (1986).

[4] D J Dodds, D M F Chapman, J C Osler and W C Risley, Minimizing instrument effects in an ocean bottom seismometer, Canadian Acoustics, 22(3), pp161-162 (1994).

[5] S R Bratt and S C Solomon, Compressional and shear wave structure of the East Pacific Rise at 11°20'N; constraints from three-component ocean bottom seismometer data, J. Geophysical Research, 89(B7), pp6096-6110 (1984).

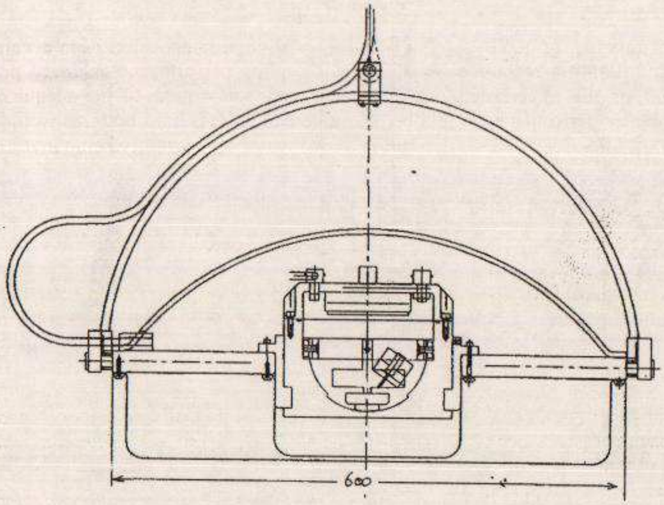

Fig. 1: Drawing of the DERA geophone sensor unit.

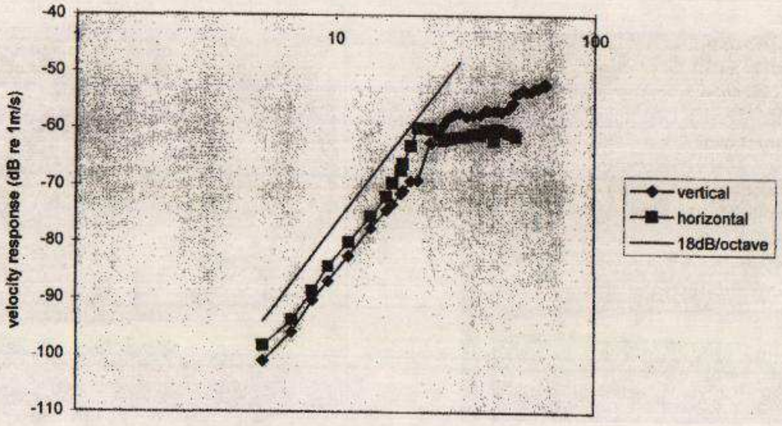

Fig. 2: Velocity response of geophone sensor unit to internal shaker.

a) b)

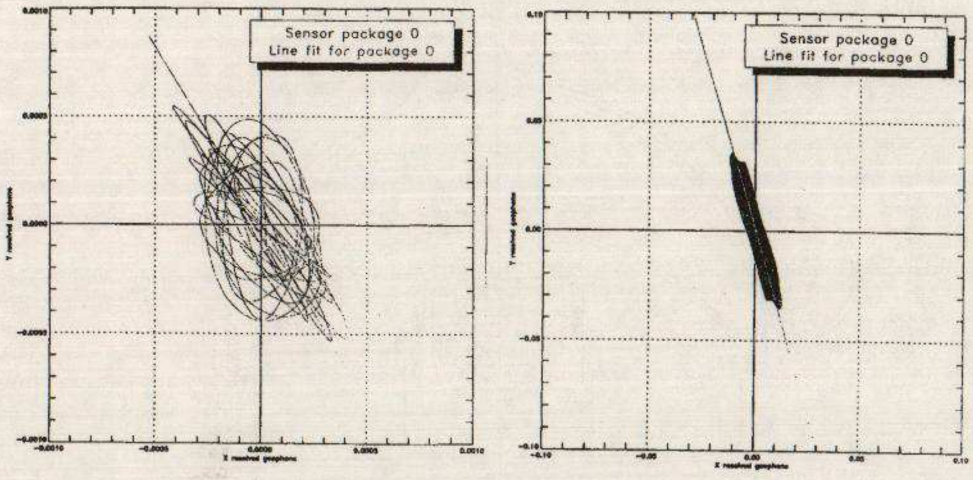

Fig. 3: Locus of measured medium velocity due to projector tones: a) 11Hz, b) 72Hz.

a) b)

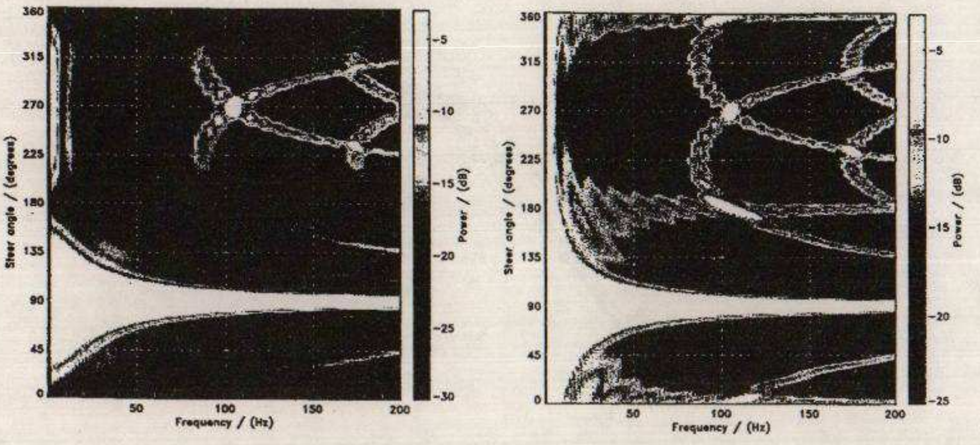

Fig. 4: Theoretical response of V-shaped array: a) horizontal component of geophones, b) hydrophones.