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Techniques for achieving dynamic stabilisation of a sonar array platform

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Abstract
The problem of compensating for the movement of a tow-fish carrying a narrow-beam sonar array is addressed. The aim is to steer the beam at a precise angle of incidence with respect to the sea bed and to maintain this by monitoring the pitch of the tow-fish and then adjusting the steered angle electronically in real time. In the application discussed here, the array is operated in conjunction with a hydrophone streamer deployed behind the tow-fish, but the problem is a general one applicable to any sonar platform.

1. Introduction
In most sonar applications the stability of the platform on which the transducer array is mounted is of fundamental importance. This is because the locations of sound sources or targets generally need to be fixed accurately. The stability is particularly problematical when the platform is a tow-fish because in addition to having its own dynamic instabilities the motion of the towing vessel can be transferred to it. In this paper the problem addressed and the various solutions considered relate to the scenario of Fig. 1, which shows the deployment of a tow-fish and a hydrophone streamer behind a ship. This was the arrangement used in a sea trial carried out during August 1994 off the coast of Brittany, France, as part of a project called REBECCA funded by the Commission of the European Communities [1, 2]. The aim was to attempt to characterise sub-bottom layers using two parametric arrays mounted in the tow-fish. The first, made by the Technical University of Denmark (DTU), operated in a depth-sounding mode and detected back-scattered signals from the sea bed and sub-bottom layers; the second, made by Loughborough University of Technology (LUT), operated in a phase-steerable mode and used the streamer to detect forward-scattered signals. Although stabilisation is discussed in terms of this system, the problem is a general one which may be solved by applying the same techniques.

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Fig. 1. Deployment of a parametric sonar array and hydrophone streamer
In this application a knowledge of the precise angle of incidence of the transmitted sonar beam at the sea bed is necessary. At the time of the trial it was not possible to stabilise the tow-fish in real time. The array was mechanically offset by $10^\circ$, $15^\circ$ or $20^\circ$, as shown in Fig. 2, and the beam could be steered electronically in the fore-aft plane through $\pm 18^\circ$. Sensors attached to the array monitored the pitch, roll and depth of the tow-fish for off-line analysis. The requirement now is to use the outputs of these sensors to correct in real time for at least some of these instabilities. Since the beam cannot be steered athwartships, no correction for roll is possible but if the roll angle of the fish exceeds about $3^\circ$ the forward-scattered signals would not be detected by the hydrophone streamer and it would be appropriate to cease transmission for such angles. For any pitching of the fish, the aim is to alter the beam angle dynamically so that the angle of incidence at the sea bed remains unchanged.

The angle of incidence can also change if there is any variation in the slope of the sea bed. So a practical stabilisation system has to detect the precise pitch and roll of the fish, monitor the slope of the sea bed, then make appropriate corrections, all in as near to real time as possible.

![Diagram](image)

Fig. 2 Deployment of electronically steered parametric array in a tow-fish

2. **Ship and tow-fish motion**

Any variations in the orientation of the array in the tow-fish may be attributed to the movement of the ship. These variations are generally oscillatory in nature, with fairly regular cyclic periods. Most ship motion may be defined in terms of three rotational modes around three mutually perpendicular axes and three transitional modes along these axes, as shown in Fig. 3. Movement in the fore-aft plane may be defined in terms of a rotational mode, *pitch*, and the two transitional modes, *surge* and *heave*. Pitch is a rotation about an axis shown perpendicular to the plane of the figure; surge is linear horizontal movement along the length of the ship; heave is linear vertical movement. Any movement in the plane mutually perpendicular to the fore-aft plane (i.e. the port-starboard plane) may be defined in terms of *roll*, *sway* and *heave*. In addition, there is a sixth degree of freedom, *yaw*, which is rotational movement about the vertical axis. Movement of the tow-fish is defined using an identical reference system. Pitch, surge or heave of the ship results in a tugging action of the towing cable, which may be translated into pitch, surge or heave of the tow-fish. The degree of movement in each of these is
dependant on the tow-fish's own hydrodynamic properties, which should compensate for most of the translated movement. Yaw, roll and sway movements in the ship are likely to introduce some sideways movement into the cable tugging action. The effect this has on the translated movement is again dependant on the tow-fish's dynamic properties.

Fig. 3 Movement in rotational and transitional axes defining ship motion.

Tow-fish movement in either the surge or heave axis should not affect the sea bed incidence angle. But movement in the heave axis would change the area of insonified sea bed, which in turn could mean a loss or reduction of the scattered signal. Assuming a water depth of 100m, a tow-fish depth of 10m and a sea-bed incidence angle of 20°, the centre of a forward-scattered signal would reach the streamer (at the same depth) 65.6m behind the tow-fish. A 2m downward heave of the tow-fish would cause a signal to arrive 64m behind the tow-fish. With a hydrophone spacing of 4 m it is not likely that heave would have a serious effect. A similar calculation may be performed for a 2° pitch of the tow-fish. The resulting sea-bed incidence angle of 22° (assuming a downward pitch) would produce a horizontal displacement of the scattered signal along the streamer. In this case, the centre of the received signal would be 72.7m behind the tow-fish, which means a horizontal displacement of approximately 7m. Angular variations greater than this could result in failure to capture all of the forward-scattered signals and a loss of precision in the incidence angle, so impairing the system's operation. Movement in either the roll or yaw axes of the tow-fish results in a sideways displacement of the effective sonar *foot-print* (the area of the insonified sea bed). This gives a similar displacement in the area insonifying the hydrophone streamer. A 3° beam has a *foot-print* width of only 10 m at the streamer (assuming the geometry above). An angular movement of the tow-fish in either the roll or yaw planes of anything greater than ± 1.5° could result in a complete loss of signal. Data from a sea trial which took place off the coast of Brittany, France, in August 1994 are shown in Fig. 4. The plots shown represent the pitch and roll of a towfish that was deployed behind the French oceanographic survey vessel *Le Noroit*. They were obtained from an area where the water depth was about 100 metres. Angles above and below the dotted lines resulted in a complete miss of the forward-scattered signals at the hydrophone streamer. Errors within these limits in the pitch plane still resulted in an error in the required sea bed incidence angle.
3. Stabilisation methods
Various methods of stabilisation and compensation have been considered [3]; these include the use of mechanically stabilised platforms, electronic stabilisation and discontinuous transmissions. Stabilised platforms have been widely used with sonar systems for many years. They usually incorporate a highly responsive platform that is physically moved to compensate for any movement of the ship on which it is mounted. This requires a high degree of mechanical precision and real time processing but can provide a high degree of stability in three rotational planes of movement.

Mechanical stabilisation was considered uneconomic and hence a compromise was made by towing the system in a relatively stable tow-fish and electronically steering the array, although this was only practical about one axis, here the pitch axis, i.e. in the fore-aft direction. The ability to steer the transmission dynamically in this way allows transmission at a variety of angles with respect to the seabed. Sensors were used to record the tow-fish attitude so that pitch corrections could be made off-line, provided that the combined steered angle plus pitch error did not lead to the signals 'missing' the receiving hydrophone streamer aperture. The achievement of real time electronic stabilisation is the theme of future work on this project.

The introduction of phase differences in the signals applied to the staves of the array can be used to steer the beam away from the transducer array's normal transmission axis. The beam can be steered through a sector or in a constant direction. In the case of the LUT array operating at its resonant frequency of 75 kHz, for example, a 100 Hz interstave difference corresponds to a 36° sector sweep in 10 ms. When operating in its parametric mode, primary frequency signals of 72.5 kHz and 77.5 kHz are summed and applied to the 13 staves to provide a fixed steer angle of...
the 5 kHz secondary frequency signal. All the waveforms are stored in memory and applied under software control to the staves with the correct phase relationships. The interstave phase relationship defining the angular sector start point allows each stave's transmission to be phase coherent at the instant of crossing the array's transmission axis, i.e. normal to the array's face. The hardware of the system allows the individual addressing of eight separate sections of the available memory which store the required waveforms to provide a series of phase-steered signals at a range of angles. When the sensors attached to the array detect a change of pitch, the appropriate waveform is selected and the beam is therefore steered to compensate for the movement. A series of eight signals allows near-instantaneous correction of the beam direction due to the sensed movement. With eight possible angles and a total phase steer capability of ±180°, the angular separation of the beams is 4.5°.

As stated above, the present array configuration allows steering only in one plane, therefore no compensation can be made for roll; beyond a roll angle of about 1.5° the scattered beam does not intercept the streamer. This has led to the notion of a fire criterion, which means that the transmission is disabled until the array is sensed to be aligned correctly. The advantage of this technique is that the amount of spurious data is limited. The system being developed uses both phase steering and discontinuous transmission.

A further consideration is the problem of alignment of the sonar beam and the streamer when the sea bed is sloping and a number of methods have been studied to determine the slope. The simplest method is by depth sounding, which can be done by periodically steering a primary frequency beam vertically downwards. A more complex method is to steer two primary frequency beams at different angles, say one slightly fore of vertical and one slightly aft of vertical, and then measure the time difference, which in turn allows the slope to be determined. A suitable way to do this is to correlate the envelopes of the two back-scattered signals; the two narrow beams would make the array appear like a Doppler sonar but instead of measuring a frequency difference, a time difference is measured. The method is therefore similar in principle to the operation of a correlation velocity log.

4. Conclusions
Trials held both in Scotland and France have established the versatility and usefulness of dynamic beam forming for generating a range of signals at both normal and non-normal sea-bed incidence angles. Further work leading to the real-time correction of attitude errors due to sea movement of a tow-fish, or indeed to any sonar platform, is being continued as part of an international project being funded by the European Commission, with partners in the United Kingdom, India and Greece.

Attitude sensors can be used to monitor errors in orientation of the tow fish due to sea movement. Selection under software control of up to eight separate waveforms to provide various transmission angles can then be made, so allowing a real time correction in one plane. Computer simulations have demonstrated that ±10° pitch error can be corrected to within 1.4°, well within the parametric signal beam width of 3°.

Discontinuous transmission techniques may also be employed to reduce the effect of misalignment due to roll of the tow-fish. This would restrict parametric transmissions to times of the most likely reception of forward scattered signals by the hydrophone streamer. The combined effects of discontinuous transmission and dynamic beam steering should lead to a considerable improvement in the operation of a parametric sonar system for sea bed and sub-sea bed profiling and characterisation.
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