Proceedings of the Institute of Acoustics

ENHANCED PROPAGATION IN A FOAMY MEDIUM

T V Gedrich(1), C H Harrison(1), A Baird(2) & A Cowley(2)

(1) YARD, 233 High Holborn, London WC1V 7DJ
(2) ARE(S), Portland, Dorset DT5 2JS

1. INTRODUCTION

Historically, acoustic propagation modelling in the ocean has been largely restricted to highly stylised environments: typically, the the problem is reduced from three dimensions to two by imposing cylindrical symmetry about a vertical axis through the source; the propagation medium is usually assumed to be stratified, and fully described by a frequency-independent (more often than not, range-independent) sound-speed profile. Even simplified in this manner, however, it is not always easy to see at a glance what transmission behaviour to expect in a given environment.

The problem is vastly more intractable if the water contains a localised cloud of bubbles (generated in the ocean by breaking waves or the passage of vessels, for example), for then none of the above approximations applies. Even if the basic mechanisms concerned can be modelled relatively simply, extracting predictions is far from trivial, and visualising what will happen in any given case next to impossible. Wildt (Reference 1) reproduces the following measured propagation anomalies (dB per unit distance above spherical spreading) at 5 and 25 kHz:

(1) Along wake: 10-80 dB/kyd

(2) Across wake: 300-6000 dB/kyd.

Wildt remarks: "These observations are rather puzzling."

In this paper we describe a prediction program, SWARM, which makes perfect sense of these results. Its functions are represented diagrammatically in Figure 1: from environmental data such as bubble populations at points within a coordinate grid, the program calculates local acoustic properties (absorption and volume scattering coefficients, sound-speeds and sound-speed gradients). These may of course be examined directly; but the stored parameters are also necessary for subsequent transmission loss predictions, reverberation simulations and ray plots.

SWARM's two stages are represented, for transmission loss across a wake, in Figure 2. The first picture depicts the environmental input : the wake has been partitioned into small, cuboidal volumes, within each of which a bubble population (as a distribution of bubble numbers against size) is assumed known. In the second, local absorption coefficients, volume scattering strengths and sound-speeds have been calculated at a lattice of points throughout the wake, and stored, and are being applied to a specific sonar problem.

2. CALCULATION OF THE ACOUSTIC PARAMETERS

Within the volume of the sea, large bubbles are very short-lived, rising quickly to the surface and either contributing to the scattering properties of the interface or escaping. As a result, at frequencies below ultrasound it has been found adequate to treat the remaining bubbles as lumped acoustic systems, with but one, spherically symmetric, radial, mode of oscillation. The behaviour of a bubble within this regime depends on its size as a fraction of a wavelength. At sufficiently low frequencies, the presence of bubbles will scarcely affect absorption and reverberation. They may considerably lower the speed of sound, however, by changing the bulk density and compressibility of the medium; the magnitude of this effect is, of course, governed by the volume fraction they constitute. Nearer to resonance, bubbles are driven into large-amplitude oscillation, and a much greater proportion of the incident acoustic energy is absorbed or reradiated.

SWARM follows the single-bubble analysis of R.Y. Nishi (Reference 2, in the special case $ka \ll 1$), in which he gives expressions for resonance frequency and for the damping constant as a sum of terms due to reradiation of sound, viscosity, and thermal conduction. From these it is easy to calculate the scattering and extinction cross-sections of a bubble (Figure 3). These are, of course, functions of frequency and bubble radius.

To calculate the bulk properties of bubble-laden water it is necessary to make two, apparently rather contradictory, assumptions. On the one hand, bubbles of any represented size should be so sparse that one may treat them in isolation, as above (multiple scattering, for example, is not modelled); on the other, they should be numerous enough to permit treatment as a continuum. A development along these lines can be found in Brekhovskikh and Lysanov (Reference 3), and elsewhere; our void fractions, typically of the order of 10^{-6}, lie within the window in which both of these approximations are reasonably applicable.

Given a bubble population at a "point" (or elemental volume) in the cloud of bubbles, local acoustic parameters are calculated by integration over the bubble density function (Figure 4). Typical plots of acoustic attenuation, volume scattering strength and sound-speed as functions of frequency are shown in Figures 5-7.

3. RAY TRACING

Ray plots do not contain much quantitative information, but wherever the eikonal equation is applicable (broadly, wherever the environment does not change too markedly over the distance of a wavelength) they are very suggestive and helpful images of sound propagation. SWARM generates polygonal rays (for a single frequency, of course, since the bubble cloud is highly dispersive) based on the finite difference formula:

$$d(n\mathbf{e}) = dl \cdot \text{grad } n, \quad \text{where } l = \text{path length}, \; n = c_0/c, \text{ and } \mathbf{e} = d\mathbf{x}/dl.$$

Below resonance (actually a band of resonances, since there are bubbles of many sizes), the speed of sound is considerably lowered; at frequencies above, increased (Figure 7).

Orthogonal projections of these three-dimensional ray paths, strikingly refracted within the bubble-cloud, offer a very immediate representation of the physics. Figures 8-12 show typical ray paths (colour-coded for intensity in the original) through a confected twin-lobe wake. The ranges involved are much smaller than is usual in propagation studies, so the curvatures visible really *are* extraordinary: any bubble-cloud as localised as a wake can give rise to extreme sound-speed gradients. In these plots, a constant sound-speed was assumed outside the wake, but a sound velocity profile may be defined (as well as a temperature distribution within the wake).

4. TRANSMISSION LOSS

In regions, and at frequencies, of highest absorption, sound is attenuated beyond detection in the space of a few metres. In this situation, only short-range propagation-loss predictions are likely to be of interest, and a simple spherical-spreading-plus-absorption formula - in effect, ignoring the sound-speed variation - is often perfectly adequate. Low absorption and considerable ray-curvature can coexist at certain frequencies, however, and over longer distances the simple formula may be seriously misleading. Returning to Figure 8, for example, a shadow zone is perfectly evident, even without benefit of the third dimension; and there is ducting in Figures 10-12, and between twin bubble trails in Figure 9. These plots also suggest the possibility of focussing effects.

SWARM estimates the true transmission loss (taking account of refraction) by projecting a number of rays from the source, each representing a proportion of the transmitted power, and summing their contributions, appropriately weighted, at the receiver.

The power a given ray represents initially depends on the angular spacing between it and its neighbours at the source - the area on the unit sphere it represents, in fact - and the directivity index applicable to it. At the receiver, this is diminished by the absorption suffered *en route*. About the receiver, a target area, more or less orthogonal to the incident rays, is defined. Each ray passing through this area is deemed to make a contribution to the received signal based on the power it "bears" on arrival, the area the target presents to its direction of incidence, and the receiver's directional response. At present, the total is calculated as a power sum, but coherent processing would also be possible.

It is in this area that SWARM makes its most striking, often counterintuitive predictions, and provides an illuminating theoretical model for the many discordant observations in this area. Ducting effects, in particular, can account completely for the discrepant losses reported by Wildt for propagation along and across a wake.

5. REVERBERATION

SWARM calculates monostatic reverberation as a power sum of surface reverberation, "background" volume reverberation (that not due to the bubble-cloud), and bubble scattering. Bottom scattering is not considered. The first two terms of the sum are estimated in a completely standard way (see Reference 4, for example). Bubble scattering is treated volumetrically: the wake is divided into elemental volumes, each of which makes a contribution based on the local volume scattering coefficient, transmission loss, transducer directionality, pulse length and source level, and so on. Transmission loss is estimated using the straight ray algorithm, where four round-trip paths (combinations of direct and surface-reflected one-way paths) between the source/receiver and the scattering element are considered.

A typical situation in which this algorithm might be exercised, and representative output, are shown in Figure 13. Three phases are clearly visible in the reverberation level time-history. At first only the background volume reverberation is detected, then we see the gradual onset of bubble reverberation, and finally surface reverberation, beginning with a sharp glint, and falling off unevenly as the returns pass through sidelobes of the beam.

6. CONCLUSIONS

The foamy medium acoustic prediction program, SWARM, is still under development, but even in its current state, on a relatively simple theoretical basis, it can model, with considerable success, propagation and scattering within bubble-clouds. Already it has greatly improved our understanding of these phenomena, and provided a convincing explanation of the disparity observed between propagation anomalies along and across a wake.

This work has been carried out with the support of the Procurement Executive, Ministry of Defence.

7. REFERENCES

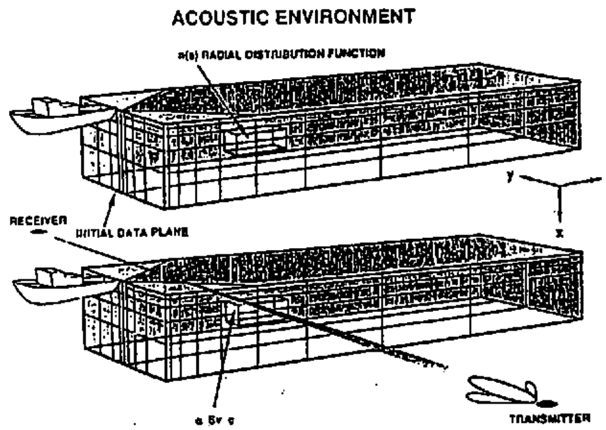
1. Wildt, R.; Physics of Sound in the Sea - Part IV: Acoustic Properties of Wakes; Gordon and Breach Science Publishers.

2. Nishi, R.Y.; The Scattering and Absorption of Sound Waves by a Gas Bubble in a Viscous Liquid; Acustica, Vol.33, No.2 (1975)

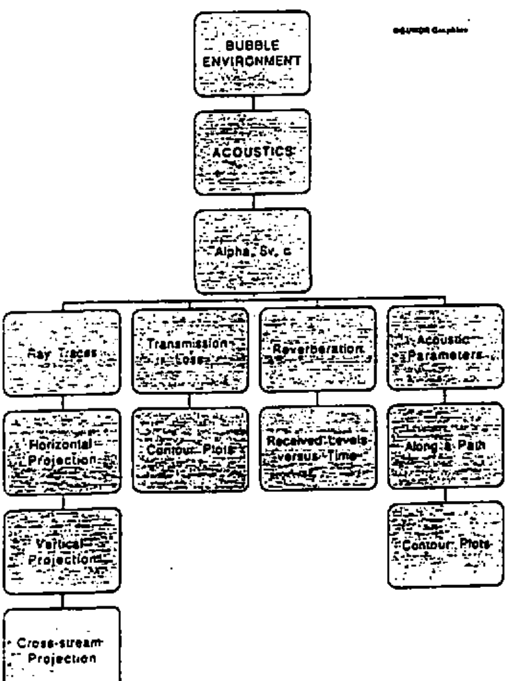
3. Brekhovskikh, L., and Lysanov, Yu.; Fundamentals of Ocean Acoustics

4. Urick, R.J.; Principles of Underwater Sound; McGraw-Hill, 1983.

ENHANCED PROPAGATION IN A FOAMY MEDIUM



2.



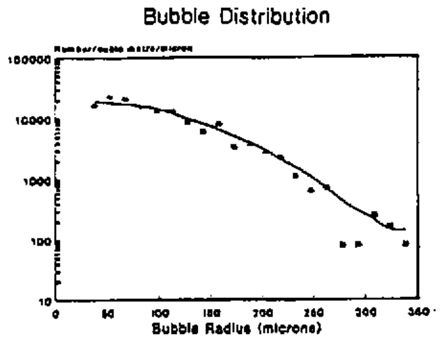
1.

$$\sigma_s = \frac{4\pi a^2}{\left[\left(\frac{f_r}{f}\right)^2 - 1\right]^2 + \delta^2}$$

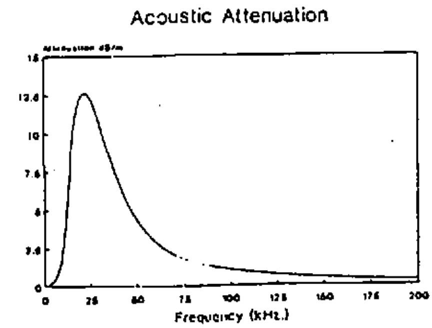
$$\delta = \delta_{rad} + \delta_{vis} + \delta_{th}$$

3.

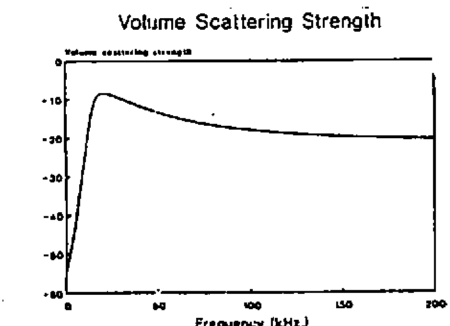
ENHANCED PROPAGATION IN A FOAMY MEDIUM



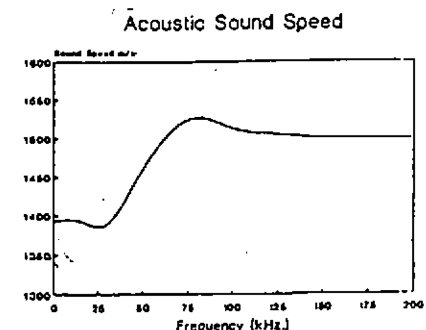
4.



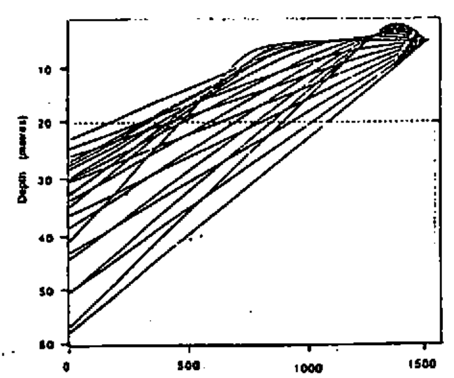
5.



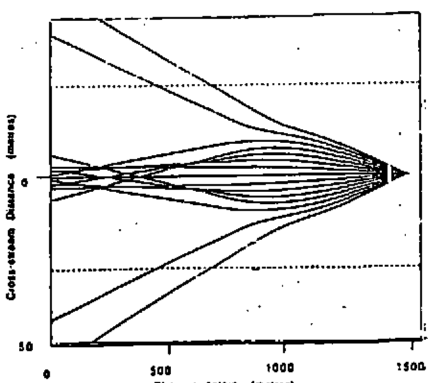
6.



7.

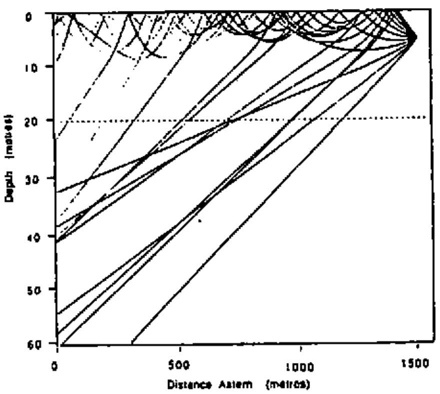


8. Vertical Projection
Above Resonance

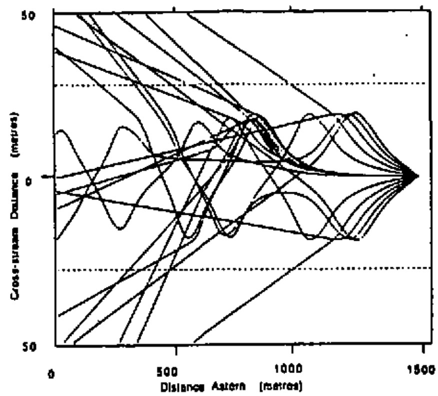


9. Horizontal Projection
Above Resonance

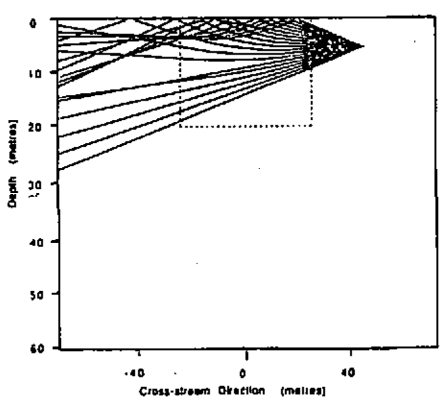
ENHANCED PROPAGATION IN A FOAMY MEDIUM



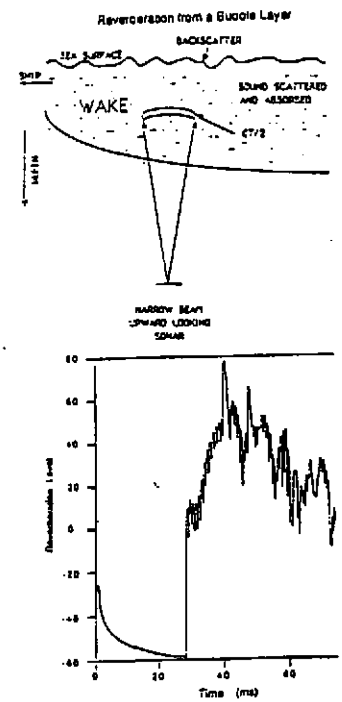
10. Vertical Projection
Below Resonance



11. Horizontal Projection
Below Resonance



12. Cross-stream Projection
Below Resonance



13.