Proceedings of the Institute of Acoustics

HEAT CONDUCTION, FISH AND OCEAN SOUND ABSORPTION

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ABSTRACT

Dr Stephens' interest in heat conduction is reflected by contrasting some heat conduction effects in atmospheric and ocean acoustics. We concentrate on the oscillating heat transfer between the swimbladder gas of a fish and the surrounding fish tissue, which, together with loss in the tissue itself, allows propagating sound to be absorbed by dispersed numbers of fish. Shallow-water evidence comes from the long-term measurements off Perranporth, and deep-water evidence comes from the recently-reported analyses of surface-duct transmission. Unfortunately support from other workers is still largely speculative or unreported, but the importance and widespread nature of this attenuation effect should now be generally recognised.

1. INTRODUCTION

This paper is in memory of Dr R W B Stephens, whom I first met when I joined Imperial College as an undergraduate in 1947. At first he appeared to be our stern taskmaster, but soon metamorphosed into the kind and gentle Ray Stephens or Steve, always helpful and mindful of our interests. He was a man who always took on far too many tasks, and then managed to cope with them all working at a tiny cleared corner of the desk in his cluttered office. There was one disgraceful occasion when members of his research group, in his absence, decided to help by sorting out the cupboards in this office. Empty date boxes were removed, those with few dates remaining were kept, single slippers without a partner were discarded, and conceivably some items were thrown out that should not have been. The next morning a worried Steve was sighted as he checked through the contents of the college dustbin.

My main subject and title are chosen to cover matters of real importance and yet to provide a connecting link or links, not entirely artificial, with the eminent scientist we are remembering here. In fact Dr Stephens was a classical physicist, coming only quite late to his concentration on acoustics, and his 1934 PhD thesis investigated heat conduction in insulating materials.

For sound propagation in air the best-known effect of heat conduction concerns the attenuation of plane waves in free space. This conduction lines up with the propagation direction and proceeds from condensation peak to rarefaction trough, the loss produced being comparable to that of viscosity. Within Stephens' research group I was investigating, both experimentally and theoretically, the rather larger attenuations encountered when the propagation is within a tube, and the heat transfer is between the contained gas and the tube wall [1,2]. In Section 2 we will continue this story, but transfer to the liquid medium.

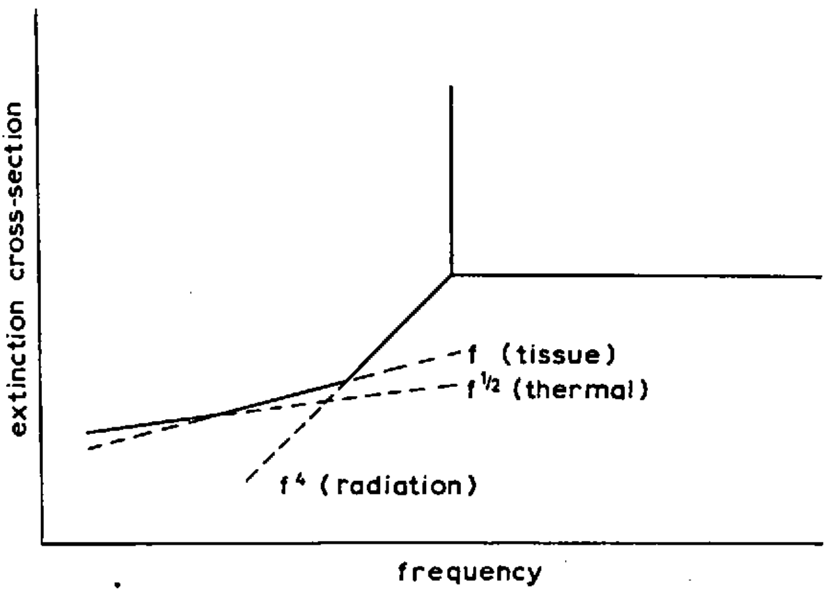

Fig 1 Schematic for the extinction cross-section of a bladder fish

2. ACOUSTIC HEAT CONDUCTION LOSSES WITH FISH

In underwater acoustic propagation the classic heat conduction effect is again the attenuation of plane waves in free space, with the same loss mechanism as in air. But this time the result is much smaller than that due to viscosity, which is itself much smaller than other causes of attenuation (such as various chemical relaxations) and also much smaller than the corresponding attenuation in air. Nevertheless heat conduction is very important in ocean sound propagation through its action in the swimbladder or gas-filled sac found within many fish.

This action may be explained by reference to Figure 1, taken from Ref 3, noting that it is the extinction cross-section which controls the attenuation. The spring factor of the gas combines with the inertia of the surrounding water plus fish tissue to give a resonance at a surprisingly low frequency, typically a few kHz. This is represented by the Figure 1 spike, which actually has a finite width as described by its Q value. The contributions to the Q value depend on the frequency, depth, bladder shape etc and we will quote typical values for the three chief mechanisms. Radiation damping due to the scattered energy gives Q_r about 40. Thermal or heat conduction processes mean that the gas oscillations within the bladder are neither fully adiabatic nor fully isothermal, producing losses with Q_t about 25. Further losses are associated with the cyclic deformation of the fish tissue, Q_f being about 10. By taking the harmonic sum of these Q values we determine the overall Q as about 6. Notice that the direct loss mechanisms are more important than the radiation mechanism, a fact that is exploited in Section 3.3. We will admit that for the purpose of this paper we have shown some favouritism in giving the star billing to thermal conduction rather than fish tissue.

Well above the resonance frequency the extinction cross-section is lower, and is mainly due to scattering. Well below the resonance frequency it is much lower, and Figure 1 shows that thermal effects can predominate.

If we have propagation through a dispersed collection of fish the sound will be attenuated because of the summed losses at the individual fish: this may be compared with trying to look through a mist. Usually the main contribution will come from fish of a size that is near resonance at the frequency of the sound. But the spectrum of fish size can be both steep and bumpy and in principle there can be significant off-resonance contributions, eg if there are very large numbers of fish of a size smaller than the resonance size.

3. EVIDENCE FOR ATTENUATION DUE TO FISH

3.1 Attenuation through Shoals

When echosounding in shallow water the bottom return is normally very strong. But if a shoal of fish is interposed between the echosounder and the bottom the return from the latter can often be seen to weaken, and sometimes to disappear altogether. This implies that the attenuation on the two-way vertical path can sometimes be very high indeed. We are of course dealing here with tightly-packed aggregations of fish, having separations equal to a few fish lengths. But this is not the case for the rest of our evidence below, where in consequence the effect only shows up over much longer horizontal paths.

(As an aside, in 1954 the writer was so impressed by the large number of biological returns seen when echosounding that he could hardly imagine they could fail to affect the long-range propagation in some way!)

3.2 Perranporth Shallow-Water Results

The best evidence comes from the very extensive data taken off Perranporth, over typical distances of a few tens of km [4]. During the day the fish are mostly in shoals and cannot scatter and absorb independently. But at night the shoals break up and the dispersed fish can cause large losses, as illustrated in Figure 2. The evidence from these diurnal changes is supported by results on range dependence, seasonal dependence (day and night), wind dependence, and observed attenuation in two-way transmission or sonar records. Such sonar records are possible because , despite the predominance of absorption, sufficient sound is scattered for the fish to paint interesting pictures of themselves. The example in Figure 3 shows the time history in a single beam 2° wide, with sardines (alias pilchards) at the shorter ranges and sprats at the longer [5]. Records of a similar type were the main subject of the writer's RWB Stephens Lecture a few years ago [6].

3.3 Surface-Duct Results

The recent Ref 7 extends the evidence into deep water, albeit for the surface duct with depths of the order of 50m. Figure 4 combines data from both continuous-wave and explosion sources, in both the NE Atlantic and Mediterranean. If there is an attenuation the lost energy has to go somewhere. At 7.5 kHz the attenuation is due to weak scattering at the sea surface, there is no direct dissipation of energy, and the escaping energy passes at a shallow angle through the region beneath the duct. Relative level ("theory") calculated from attenuation rate agrees well with experiment. At 3.25 kHz a similar theory leads to a mean 7dB discrepancy in level,

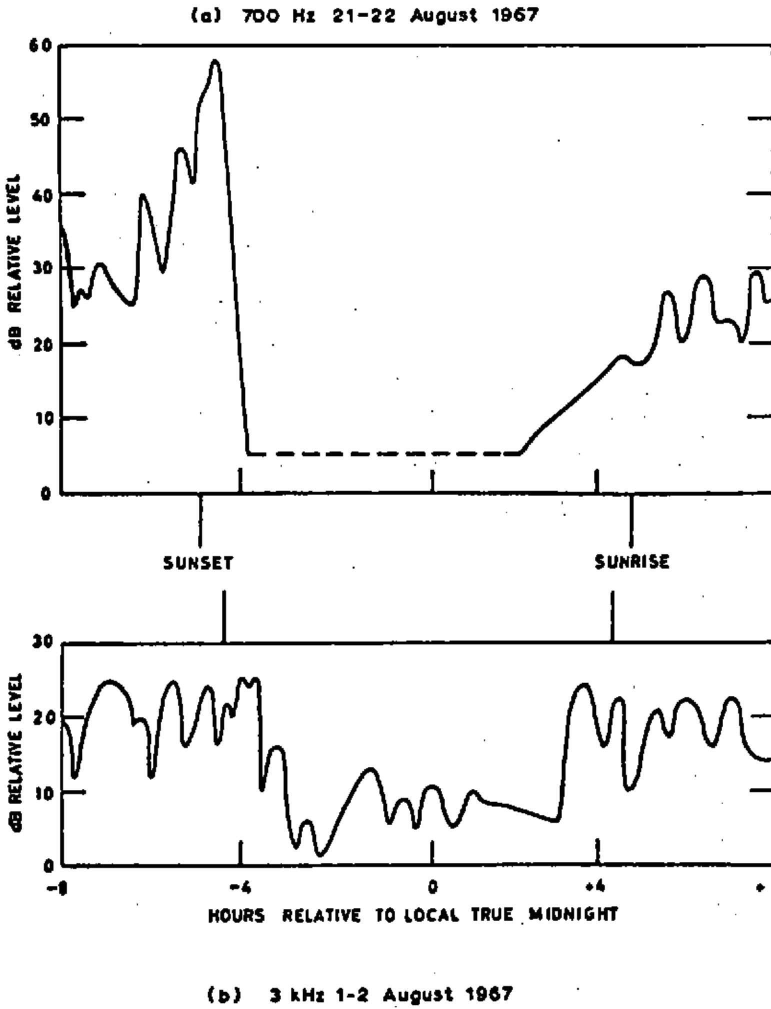

Fig 2 Examples of diurnal changes in fish attenuation illustrated by pulse envelope curves at 23 km

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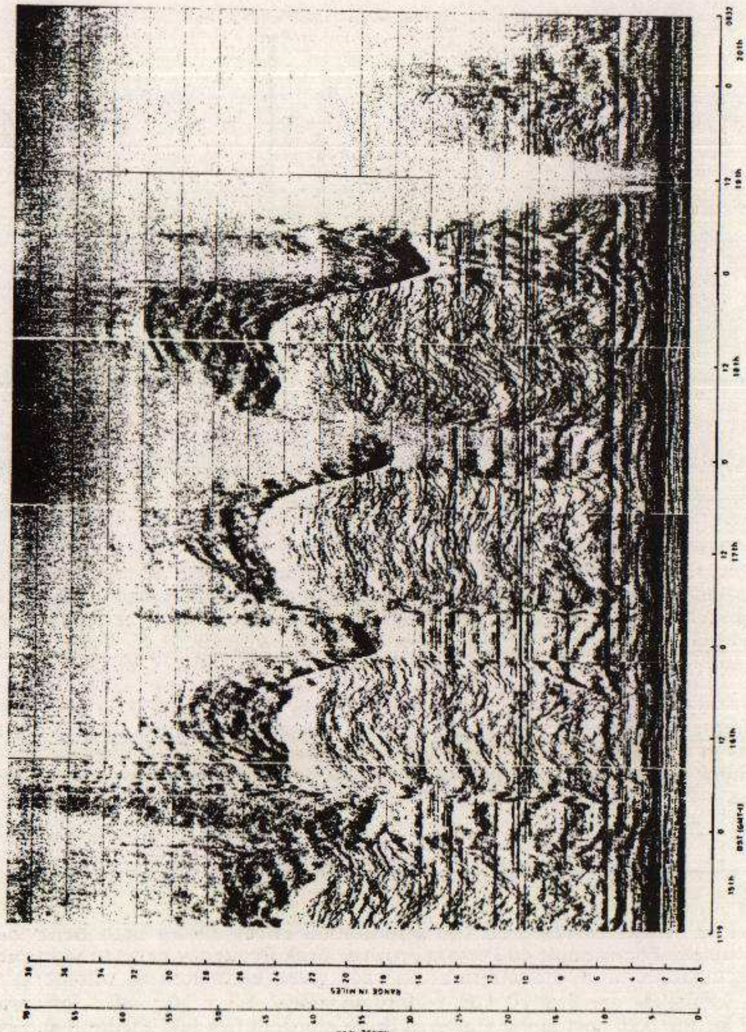

Fig 3 A 2 kHz echo-ranging display for 15 - 20 May 1967

corresponding to a factor 5 in attenuation rate. The explanation is that at this frequency the main attenuation is due to fish, it is predominantly an absorption, and even the little energy that is scattered escapes at steep angles and so contributes very little to the below-duct level.

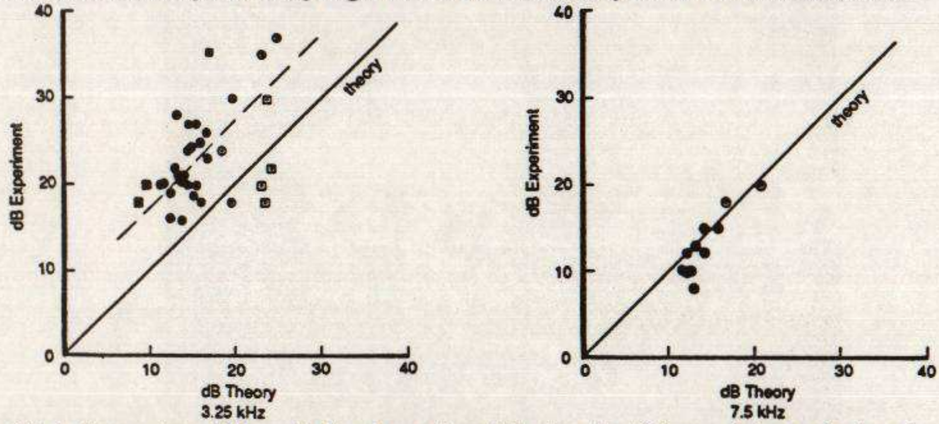

Fig 4 Comparison of theoretical and experimental values for difference between duct and below-duct levels

3.4 Other Work

As one who has reported and generally championed the cause of fish attenuation the author is still out on a limb, though it is now a very stout and comfortable limb. Other evidence is fairly widespread - but it tends to be merely hearsay or anecdotal or speculative or not properly reported. Adding everything together there are suggestions of effects in the Gulf of Mexico, NW and NE Atlantic, North Sea, Baltic, Mediterranean and in Chinese waters.

For the latter we can cite Shang [8], with a typical "trap" frequency 630 Hz at which there is excess attenuation of about 20 dB at 28 km. Trap frequencies vary from 0.5 to 2 kHz, all for shallow water in the summer. This description is characteristic of fish attenuation, which is confidently thought to be the cause, though this is the present writer's view and not necessarily that of Shang.

4. SIGNIFICANCE

4.1 Significance for Fisheries

In fisheries and fisheries research the attenuation effect allows both behavioural and population studies. For example off Perranporth the peak frequency helps in sizing and in species identification, and the attenuation rate gives estimates of numbers. Typical population densities are 3×10^{-3} m^{-3} for sardines, 1.3×10^{-2} m^{-3} for sprats and 5×10^{-2} m^{-3} for the 5cm post-larval stages of these clupeoid fish [4]. Figure 5 shows sardine population estimates through the seasons for neighbouring areas [9]. The graph of total catch cannot be quantitatively related to the other two graphs but an independent check from counting pilchard eggs suggested 4×10^{-3} m^{-3} as a typical figure.

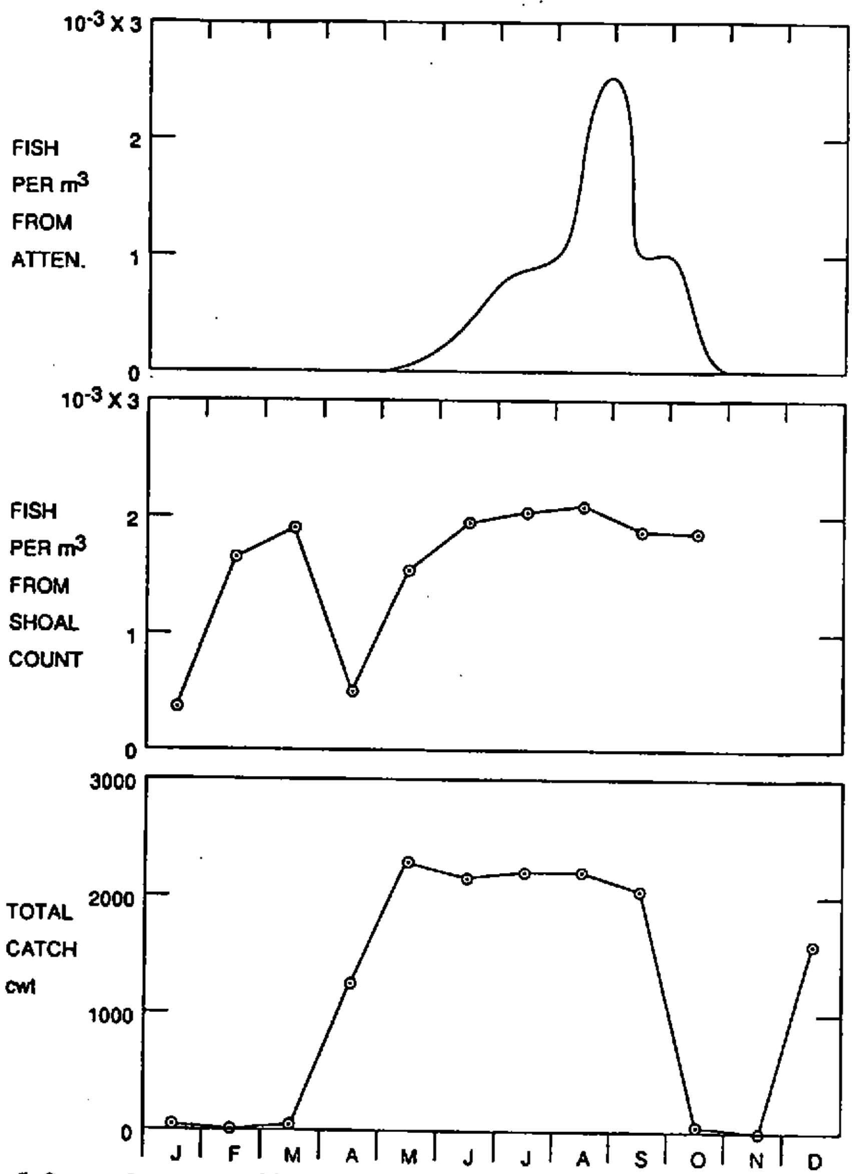

Fig 5 Seasonal estimates of fish density from attenuation, fish density from sonar shoal count, and recorded pilchard catch; all averaged for 1967 and 1968

4.2 Significance for Acoustics

The new evidence for deep water suggests that significant fish attenuation may be even more widespread than previously realised. Sufficiently great populations are only likely to be encountered in shallow water and in the upper layers of the deep ocean, such as in surface ducts. It has been suggested that the more biologically productive ocean regions tend to occur north of about 30° N (latitude of New Orleans, Canaries, Kuwait, Shanghai) or south of about 30° S. A more detailed mapping, related to the hydrography and originally due to HU Sverdrup, appears on p 135 of Ref 10. Even within such regions the temporal and spatial occurrence of significant attenuation is likely to be very patchy, fish don't always stay in the same place.

Knowing about the effect can help in general understanding of ocean sound propagation, in resolving discrepancies including curious diurnal effects, and in preventing overconfidence in prediction accuracy. As a special point we wish to draw attention to doubts about earlier literature estimates of other quantities such as surface reflection loss, because no allowance had been made for fish attenuation. These doubts should be taken in parallel with those arising from underestimation of the pH-dependent attenuation due to boron relaxations [11,12].

5. CONCLUDING REMARKS

Fish attenuation is already too well established to need any conclusion on its reality, but we do believe its importance and potentiality for upset are insufficiently realised.

6. REFERENCES

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