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EXPERIMENTAL PERFORMANCE OF FIBRE OPTIC HYDROPHONES

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1. INTRODUCTION

Optical Fibres exhibit microphonic properties when subjected to mechanical stress, and therefore, acoustic waves in water can be detected using various manifestations of this phenomenon. The method described here makes use of the variation of optical fibre propagation constant with applied stress (Reference 1). The principal mechanisms involved are changes in fibre dimensions due to stress, and the stress optic effect, which causes a change in the refractive index. Changes in the propagation constant of the fibre can then be detected by observing the corresponding changes in the phase of coherent light emerging from the fibre. In the work described here, these phase changes, and therefore the acoustic wave causing them were detected using a Mach Zehnder heterodyning interferometer. Hydrophones were constructed from coils of optical fibre and characterised by recording their beampatterns and measuring their sensitivities, and threshold detection levels.

2. PRINCIPLES OF OPERATION AND EXPERIMENTAL TECHNIQUE

Light from a 633 nm He-Ne laser is launched into the arms of a Mach Zehnder interferometer (Figure 1). The reference arm contains an acousto-optic modulator, operating at 40 MHz. The frequency shifted first order optical beam is selected for combining with the light from the measuring path which contains a 10 m length optical fibre, wound into a coil, and submerged in water. The light beams from the two arms are co-aligned at the beam combiner A, and then impinge upon the PIN photodiode. The non-linear characteristic of this device ensures that multiplication of the two beam amplitudes takes place, producing optical sum and difference frequencies, of which only the difference frequency, at 40 MHz, is detected. This heterodyne, or carrier frequency can be displayed on a spectrum analyser at the output of the photodiode. When an acoustic pressure wave is incident on the submerged fibre, the periodic mechanical stress induces a corresponding variation in the phase of light from the fibre. After the optical mixing process at the photodiode, this phase variation appears as a phase modulation on the 40 MHz carrier. The acoustic signal can be demodulated using standard FM or PM techniques and in the present experiments a commercial VHF communications receiver was used for convenience.

Acoustic beampatterns were recorded by using the detected acoustic signal to drive the input of a level recorder, after amplification and filtering. The hydrophone coil was suspended in the water from a turntable ganged to the level recorder, in the normal way. The leads from the hydrophone were taken to a lightly constructed optical bench adjacent to the tank. Insonification of the coil was by use of a broadband projector.

Sensitivity measurements were achieved by comparing the radian deviation (as recorded on a spectrum analyser) with the output of a calibrated broadband hydrophone, situated adjacent to the fibre hydrophone. Sensitivity was defined as the radian deviation per unit of applied pressure. Assuming that the spectrum represents a pure phase modulation, then the sideband levels relative to the carrier are related to the modulation index β_m, where β_m is, by definition the peak modulation in radians. In particular, if the modulation is narrowband then only the first sidebands are significant carriers of energy, and

$$\frac{I_m}{I_s} = \frac{\beta_m^2}{2} \qquad \frac{I_s}{I_m} = \left(\frac{\beta_m}{2}\right)^2 \qquad \ldots (1)$$

where I_m is the energy of the carrier, and I_s is the energy in one of the first sidebands. Thus spectrum measurements, allied with sound pressure level observations will provide radian sensitivity at a given orientation of the hydrophone, and a given acoustic frequency. In addition, the noise performance of the hydrophone and its associated high frequency electronics can be deduced from the signal to noise ratio of the carrier, when the measuring bandwidth is taken into account. It is well known (Reference 2) that the sound pressure necessary to achieve a unity signal to noise ratio in one hertz basebandwidth is given by

$$\delta P_o = (2\gamma W_m S^2)^{-\frac{1}{2}} \qquad \ldots (2)$$

where S is the sensitivity and γ is the carrier signal to noise ratio in a measuring bandwidth W_m.

In general, the beampatterns were recorded using pulsed range gated signals, while the sensitivity measurements were made with continuous waves. This set a limit to the lowest useable frequencies of about 2 kHz, due to the presence of severe standing wave pressure effects in the tank.

It has been shown both theoretically and experimentally, that multimode fibres can be used effectively in this application, and with much the same sensitivity as single moded fibres (Reference 3). To achieve this, fibres have to be chosen in which all the mode propagation constants change similarly with pressure. The chief advantages of using such fibres at the present time are availability, cost and convenience. There are a few drawbacks as far as experimental work is concerned. The chief of these is a tendency for signal "fade" analogous to multipathing in radio reception, where the various optical modes in the fibre destructively interfere. The use of phase modulation minimizes these effects and little inconvenience is experienced in practice. However, they would not be tolerable in an engineered transducer system. The combination of multimode fibres and a heterodyning system allows relatively low quality optical equipment to be used, since the stability requirements for monomode fibres, and the environmental protection for baseband interferometers are not present.

3. EXPERIMENTAL RESULTS

Coils of optical fibre were wound using 10 m lengths, and were constrained by tight lacing (see Figure 2). These were immersed in water without encapsulation. The fibre used was a low moded small diameter (33 μ) core graded index telecommunications fibre by STC: its construction is illustrated in Figure 3. Beampatterns of two coils are shown in Figures 4 and 5, and sensitivities in Figure 6.

4. COMPARISON WITH THEORY

Low Frequency Sensitivity At frequencies low compared to coil resonances, it is assumed that the sensitivity can be obtained using a static model and depends strongly on the nature of the applied stress, which in turn depends upon the construction of the hydrophone. For the simple coils investigated, the assumption of uniform hydrostatic stress is probably close to reality, as long as the hydrophone is small compared to a wavelength: with this assumption, the phase sensitivity of a jacketed fibre can be expressed by, (Reference 4),

$$\left(\frac{\Delta\phi}{pL}\right)_J = k_o\mu L\left\{\left[1 - \frac{\mu^2}{2}(p_{12} - p_{11}\sigma - p_{12}\sigma)\right]\left[\frac{k^2(1 - 2\sigma') + 2r^2(\sigma' - \sigma)}{E'(R^2 - r^2) + Er^2}\right] - \frac{\mu^2}{2}(p_{11} + p_{12})\frac{(1 - \sigma - 2\sigma^2)}{E}\right\} \quad \ldots (3)$$

where p is the static pressure, L is the fibre length, k_o is the optical free space propagation constant, μ is the refractive index of the fibre. E is the elasticity of the fibre and σ its Poisson's ratio, E' is the elasticity of the jacket, and σ' its Poisson's ratio. p_{11} and p_{12} are the photoelastic strain constants for the isotropic medium. R is the overall jacketed radius and r is the radius of the bare fibre. In general, E' is much lower than E and R is much greater than r, and the presence of the jacket leads to an effective increase in fibre strain, and to a consequent increase in sensitivity.

Inserting typical parameter values into equation (3), the following theoretical sensitivity is obtained:

$$\left(\frac{\Delta\phi}{pL}\right)_J = -183 \text{ dB re 1 rad/}\mu\text{Pa/m for the jacketed fibre.}$$

Examination of the low frequency sensitivity of the fibre coils used in the experiments (Figure 6), shows sensitivities of -178 dB and -166 dB re 1 rad/ μPa/m, with the smaller coil showing a higher value. The reasons for the higher value are not known, but it seems likely that either the hydrostatic stress model in this case is inadequate due to the coil construction, or that the assumption of pressure sensitivity is inadequate, and that pressure gradient effects should be taken into account.

Beampatterns and Resonances While no formal analysis of the acoustic performance of the coils has been attempted, some correlation with simple models of the dynamics of the coils has been achieved. The beampatterns bear a familial relationship with those of piezoelectric free flooding rings, and similarly, resonances calculated from free flooding ring theory appear to agree broadly with experiment.

It is a reasonable assumption that the extensional, or radial modes of the coil, treated as a solid ring, would be prominent, since these involve elongation of the ring, whereas flexural and torsional modes do not. The modal frequencies of a narrow ring are given by:

$$f_s = \tfrac{1}{2}\pi \quad (s^2 + 1)^{\frac{1}{2}} \; E/\rho a^2 \qquad \ldots (4)$$

where E is the elasticity, ρ is the density and s = 0, 1, 2 etc. The fundamental s = 0 is the purely radial ring resonance.

For the coils under consideration the fundamental ring modes are calculated to be at 5 kHz and 14 kHz. The other prominent resonance is likely to be due to the water cavity within the ring. The modal frequencies of such resonances are given by Reference 5.

$$f_c = (2s - 1) \frac{c_o}{2} /(h + 2\alpha a) \qquad \ldots (6)$$

where c_o is the velocity of sound in the water column and α is an end correction, h is the length of the column, and a is the radius. Use of this equation, in conjunction with expressions for c_o and h from Reference 5 leads to fundamental cavity resonances of 4 kHz and 11 kHz for the two coils, although the figures for the large coil have to be treated with suspicion, since its dimensions are outside the limits of applicability of the theory. Comparing these major resonances with the practical results indicates some agreement: in the case of hydrophone 1 a broad resonance in the range 2.5 kHz to 5.5 kHz encompasses the cavity and ring resonances expected in the region 4 - 5 kHz. The resonance at 10 kHz is unexplained on this basis. Similarly, in the case of hydrophone 2 a peak occurs at 11 to 12 kHz which compares to cavity and ring resonances predicted at 11 and 14 kHz. The minor sensitivity peak measured at 16 kHz might correspond to a weak ring resonance. Examination of the beampatterns of the transducers provides support for this interpretation of the major resonances, in which cavity modes tend to be face sensitive, and ring modes edge sensitive.

Noise Performance, Threshold Detection Pressures and Ultimate Sensitivity

The extrapolated pressure levels in unit bandwidth at which the signal to noise ratios become unity, measured at the output of the photodiode amplifier are shown in Figure 7 and are based on Equation 2. They assume a heterodyne signal-to-noise level of 70 dB in 10^5 Hz. The ambient noise for sea state 0 is also included for comparison. Also shown is the extrapolated sensitivity for hydrophone 2, assuming a fibre length of 100 m and reasonable extrapolations of achievable heterodyne levels, and amplifier noise figures in an optimized system. As can be seen, minimum detectable pressure is below sea state 0 up to 50 kHz.

5. CONCLUSIONS

It has been shown that simple fibre coils used as hydrophones behave in a manner similar to the equivalent ceramic free flooding rings. Ultimate sensitivity of such hydrophones is very high even when conservative extrapolations are made. Knowledge of the experimental performance of these coils will enable a comprehensive model of their performance to be constructed and lead to characterization of hydrophones of different fibre configurations.

ACKNOWLEDGEMENTS

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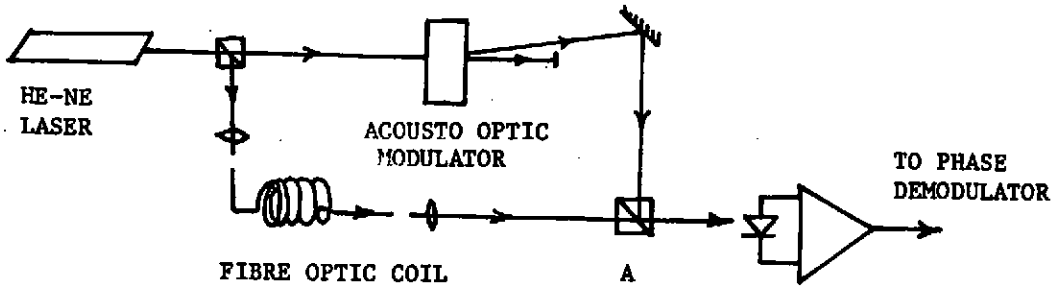

FIGURE 1 MACH ZEHNDER HETERODYNE INTERFEROMETER

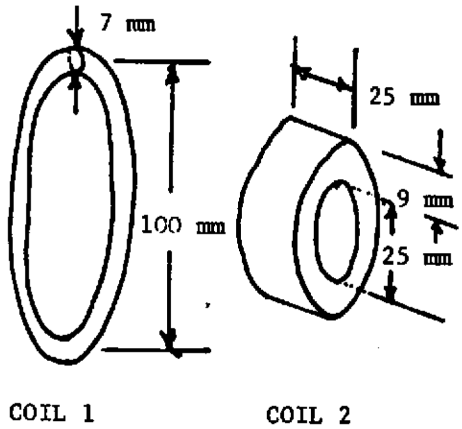

FIGURE 2 COIL DIMENSIONS

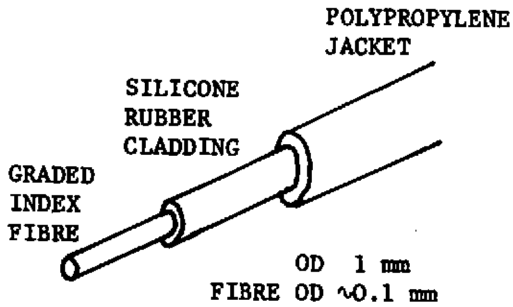

FIGURE 3 OPTICAL FIBRE CONSTRUCTION

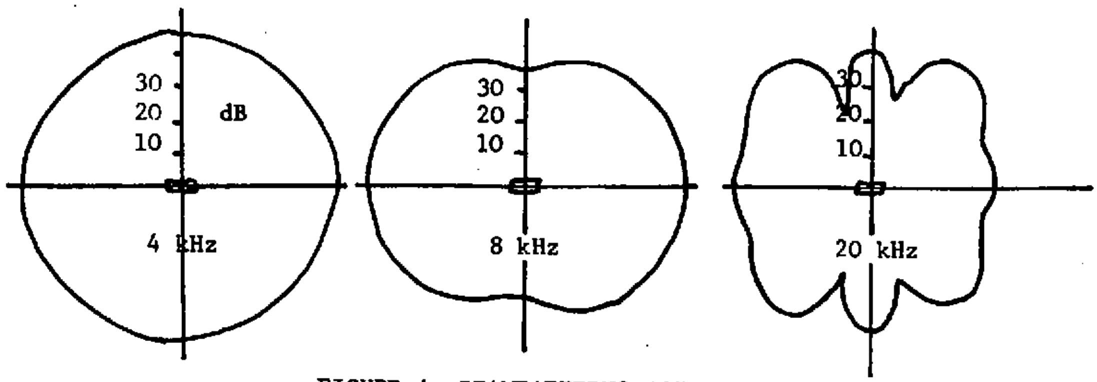

FIGURE 4 BEAMPATTERNS COIL NO. 1

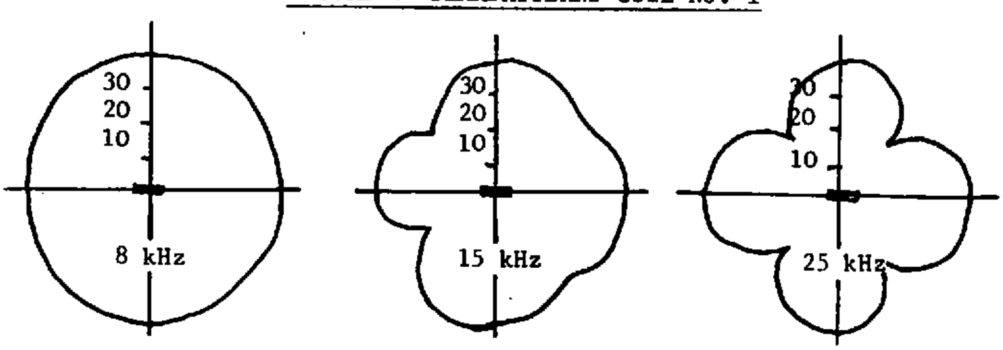

FIGURE 5 BEAMPATTERNS COIL NO. 2

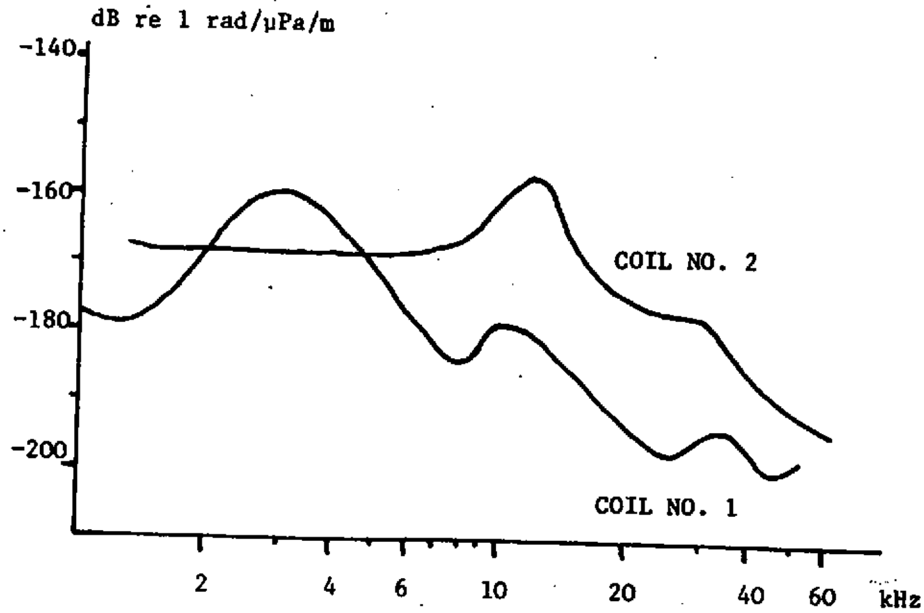

FIGURE 6 HYDROPHONE FACE SENSITIVITIES

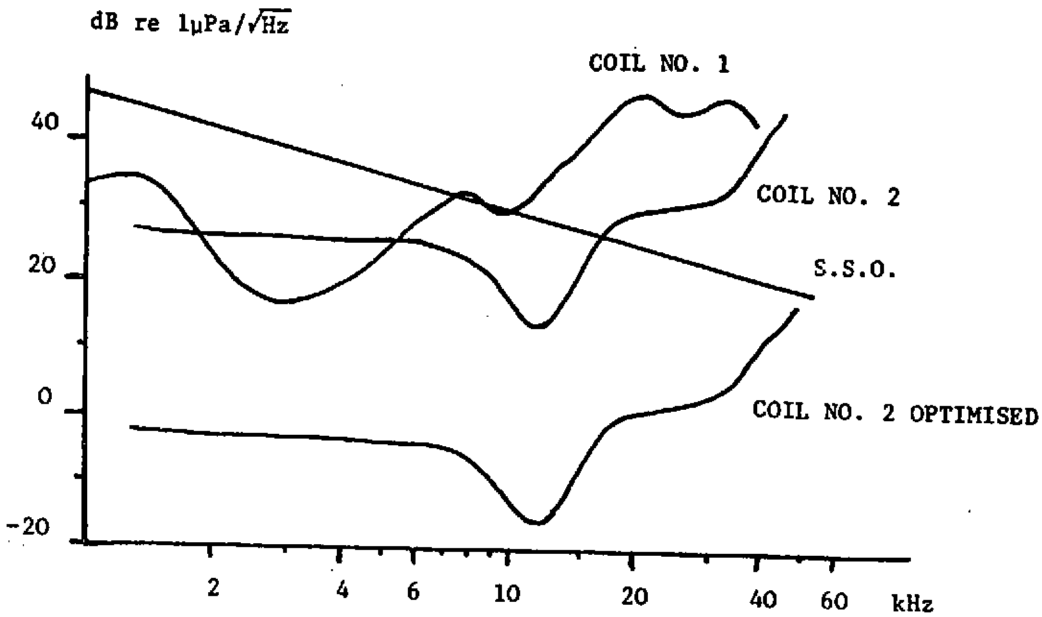

FIGURE 7 THRESHOLD DETECTION PRESSURES