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DEVELOPMENT OF A LABORATORY PROTOTYPE VELOCITY HYDROPHONE UTILIZING OPTICAL MEASUREMENT TECHNIQUES

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INTRODUCTION

Cambridge Consultants Ltd are developing a prototype particle velocity sensor. The measurement system employed is based on fibre optic technology. The objective of the project is to demonstrate that the prototype instrument has the expected characteristics and to determine its operational performance under laboratory conditions. At this stage, no attempt has been made to ruggedize its construction such that it could be operated in a true marine environment. The prototype has been constructed and is currently undergoing a rigorous assessment. Therefore, this contribution is by way of a progress bulletin rather than a final report.

Before describing our prototype instrument in detail, we examine the question of what is a particle velocity sensor and why is such a sensor desirable. Following on from this, the design approach adopted is discussed. The major components of the system are the active element to couple into the acoustic wavefield, the optical sensor to perform the measurement of the movement of the element, and electronic circuitry to drive the light sources and to provide signal processing. Each of these components will be considered separately. In addition, the complete instrument package must provide a rigid mounting for the active element and allow alignment of the optical sensor to be made. These features are discussed under the mechanical design.

TOWARDS A VELOCITY SENSOR

The concept of a velocity sensor is a slippery one and hard to define. There are two aspects to the problem; one is the advantage to be gained from a sensor which responds to a vector field associated with acoustic waves; the other is the advantage arising from the choice of the velocity field, in particular, as the vector quantity to measure.

Most conventional hydrophones respond to the acoustic pressure field. Pressure is a scalar, and thus the sensor has no inherent directionality. It alone cannot be used to determine the propagation direction of an incident acoustic wave. The well known cardioid directional response of pressure hydrophones is merely associated with diffraction effects; the beamwidth is equal to the incident wavelength divided by the diameter of the transducer. This is often a disadvantage, particularly for broadband applications such as passive sonar, where the directional response of a given system obviously varies with frequency.

A hydrophone which responds to a vector field of the acoustic wave has an inherent directionality independent of frequency, which is a distinct advantage. As a simple example, we can consider the following situation. If two pressure hydrophones are placed back to back, and the difference signal is taken, that difference signal is a measure of the pressure gradient.

Pressure gradients are a vector quantities which very with the direction of a wave. The pressure gradient along a wavefront is zero, but across a wavefront it is finite. Such a system, in fact, acts like a dipole, and has the expected cosine directional response. It is important to note, however, that diffraction effects will still occur. In order to achieve a pure dipole beam pattern independent of frequency, the device must be small compared with the smallest wavelength of interest. That is to say the individual hydrophones in the differential system must each have an omni-directional response.

Having explained the advantages of a vector hydrophone, the next question to consider, is why choose the velocity field? This can be explained by noting that the pressure field p(x,t) depends on the particle velocity field, v(x,t) scaled by the acoustic impedance of the medium. Thus,

$$p(x,t) = \rho c\, v(x,t) \tag{1}$$

when ρ is density
and c is acoustic propagation velocity.

Differentiating with respect to time, t, we have

$$\frac{d}{dt}\, p(x,t) = \rho c \frac{d}{dt}\, v(x,t) = iw\, p(x,t) \tag{2}$$

Also

$$\int p(x,t) = \rho c \int v(x,t) = \rho c\, x(x,t) = \frac{p(x,t)}{iw} \tag{3}$$

assuming a harmonic wavefield.

Hence, it can be seen that only in the case of the velocity field is the response proportional to the pressure field (1). In the case of acceleration (2) and displacement (3), the vector field is proportional to frequency and to the inverse of frequency respectively. Thus, a device will only have a directional response independent of frequency, to a broadband acoustic wave, if it responds to the velocity field of the incident acoustic wave.

Having set the scene theoretically, let us consider our implementation of the device. The device consists of an active element, which is well matched to water, and its motion follows that of the velocity field. Its motion is then tracked by a fibre optic sensor, which measures displacement. This is not ideal. The effect of the sensing element having a response proportional to the displacement of the active element, rather than proportional to its velocity, affects the minimum detectable signal, and the sensitivity, which are both inversely proportional to frequency. This is clearly a disadvantage, compared to the ideal device. However, the minimum detectable signal is smallest and the sensitivity is greatest at the lowest frequencies, where the behaviour of conventional devices is most problematical. We would seek, in a further development to replace our existing fibre optic sensor with a sensor, which could be configured to measure velocity directly, and is likely to use an interferometric technique.

ACTIVE ELEMENT DESIGN

We will now consider the factors governing the design of a mechanism that will respond to the particle motion which occurs during the passage of an acoustic wave.

The response of a body suspended compliantly in a moving fluid is discussed in general terms by Blevins (1986). He shows that there are three contributions to the force: a 'buoyancy force', an 'added mass force' and a 'drag force'.

In our case, the Reynolds number will be of order 10^{-4}, so that the flow is dominated by viscosity. Following the analysis of Lamb (1975), we find that the drag is only about 0.1% of the total force and may thus be neglected. The remaining forces are proportional to the fluid acceleration, and it is straightforward to show that if the system is forced below resonance, the response will be weak and out of phase with the external flow. Forcing above resonance, on the other hand, gives a good in-phase response. For this reason, we have chosen a resonant frequency of 3Hz as one of the design parameters.

The 3Hz resonant frequency is associated with the lowest mode of vibration. Higher order modes will therefore introduce resonances into the frequency band of interest. At frequencies above 10Hz, however, we would expect these to be strongly damped and not to present significant problems.

Design options

A number of alternative design concepts were evaluated. Initially, we considered circular membranes or diaphragms as these are similar to conventional hydrophones. A membrane is a skin of material stretched across a frame under tension, which provides a restoring force. By contrast, a diaphragm is an elastic material, clamped at the edges so that flexure of the material sets up stresses to provide the restoring force. Our analysis showed that devices could be constructed to have the required resonant frequency and with suitable dimensions.

However, to detect the motion, a beam of light would be reflected from the surface of the diaphragm or membrance using a mirror. This requirement represents the major problem with such devices. The device itself has an infinite number of higher modes of vibration in which the mirror would tilt as well as translate. Any apparent movement arising from such tilting would be difficult to detect and correct for. A further problem is that of predicting the response to an off-axis incident acoustic field.

A different approach is offered by the optical fibre whisker. A fibre firmly clamped at one end and cantilevered into the fluid will respond to an incident acoustic field. By shining light along the fibre, the motion of the tip can be followed by forming a focussed image of the end, which can then be tracked.

The advantage of this system is that it is straightforward to model. Furthermore, any higher modes of vibration of the whisker will cause no adverse effects on the measurement system. On the minus side the response is only about 60% of the fluid motion. The whisker must also be about 50cm in length, which is a significant fraction of an acoustic wavelength at the higher frequencies of interest.

To improve the response a wafer design was proposed, using a thin strip of material attached to the fibre. This presents a further advantage, in that there is now an inherent directivity in its response. However, the length of the wafer is not significantly reduced, since increasing the width of the active element increases the bending stiffness in proportion to the added mass.

The design finally adopted for the active element is referred to as the 'leaf' and combines the best features of both the previous designs discussed (Figure 1). The added mass in increased by attaching a circular disc to the fibre, which does not affect the stiffness. To achieve the desired 3Hz resonant frequency, we used a fibre of length 7cm with a 3cm diameter disc attached.

OPTICAL DESIGN

The optical design of the fibre-optic prototype sensor is based on a two-wavelength fibre-optic microdisplacement transducer developed previously by Cambridge Consultants Ltd. An optical transmitter unit launches light at each of the two operating wavelengths alternately into the input fibre giving so-called "time-division multiplexing" (TMD). (The term "light" in this context refers to radiation in both the visible and near-infrared regions of the spectrum). At the sensor head, mechanical movements of the leaf in the acoustic field are converted into changes in the relative intensities of the light at the two wavelengths. This modulated light signal returns along the output fibre to the transceiver unit, where the displacement is determined by the processing electronics from the output of the optical detector. The crucial consideration throughout the design of the optical system was the requirement to maximize the optical power throughput and hence the signal to noise ratio. Therefore, optical fibres with the largest feasible core diameter where used.

Sensor Head

The optical layout of the sensor head is shown schematically in Figure 1. The end face of the input fibre constitutes a circular source of light at the two operating wavelengths. It is imaged and magnified by lens L1 onto the plane of lens L2. Lens L2 then acts as a field lens, imaging L1 (demagnified) onto the end face of the output fibre. The input fibre (leaf) is suspended such that it will be displaced by the acoustic field, thus causing the magnified image on L2 to be displaced. A split-field filter F divides the image plane at L2 such that light at one wavelength is transmitted by only one half-field and light at the other wavelength by only the other half-field. The filter comprises, two band-pass interference filters, with the (straight) cemented boundary between the two halves being aligned at right angles to the direction of the displacements being measured. The lens L2 then collects the light from the moving image and couples it onto the output fibre.

As shown in Figure 1, the jacketed fibre optic cables which are used for both the input and output cables are terminated on the top and bottom support plates. Bulkhead couplers are used to connect from the unsheathed leaf and output fibre sections into the jacketed fibres. At every joint, there is a maximum loss of 1.0 dB in signal power. However, this loss was far outweighed by the convenience of being able to manufacture the leaf fibres separately. These fibre terminations also provide very useful system measurement points during the alignment process.

The unsheathed output fibre was wound tightly round a mandrel. The purpose of this was to reduce optical noise by ensuring that the mode structures of the optical signal at the two wavelengths were as nearly identical as possible.

ELECTRONIC SYSTEM

The electronic system consists of two major parts, the transmitter and the receiver (Figure 2). The transmitter drives the two LEDs $L\lambda1$, $L\lambda2$ sequentially at a 6kHz rate. A feedback control system uses the monitoring pin-diode Dm to maintain equal intensities at both wavelengths into the fibre F1 (the equalizing loop). The receiver itself performs two functions. Firstly, it generates the output voltages Vo1 and Vo2 proportional to displacement or particle velocity. Secondly, it maintains constant total illumination into the dector D: a feedback loop controls the drive levels to the two LEDs (the levelling loop).

The individual intensity signals at each detector can easily be separated out using a demultiplexer (Demux) synchronized to the LED pulsers. The synchronizing signals S are derived from the master clock, and applied to the two pulsers and two demultiplexers. Compared with simultaneous operation at both wavelengths, this system halves the number of detectors needed, and removes the need for filtering in front of them. It also has the technical advantage of insensitivity to detector responsivity changes resulting from temperature or ageing effects.

Receiver

The receiver assumes that equal intensities have been transmitted to the input fibre at $\lambda1$ and $\lambda2$ i.e. $I\lambda1 = I\lambda2$. Any difference in the intensities at the receiver input are therefore, as a result of the deflection of the active leaf. The receiver is required to generate Vo1 thus:

$$Vo1 = k \left(\frac{I\lambda1 - I\lambda2}{I\lambda1 + I\lambda2} \right) \tag{8}$$

proportional to the sensor movement

$$\text{So} \quad Vo1 = k' \left(\frac{V\lambda1 - V\lambda2}{V\lambda1 + V\lambda2} \right) \tag{9}$$

where $V\lambda n$ is the demultiplexed detector output voltage.

This equation sets Vo1 equal to the normalized voltage difference.

$(V\lambda1 + V\lambda2)$ is the normalizing factor which allows for variation in the absolute intensities of the light signals (due to LED or fibre effects). If we arrange for $(V\lambda1 + V\lambda2)$ to be constant, then Vo1 becomes:

$$Vo1 = k'' (V\lambda1 - V\lambda2) \tag{10}$$

This is an easy function to generate electronically because no division has to be performed.

The levelling loop forces $(V\lambda1 + V\lambda2)$ to be constant with feedback control of the transmitted intensities. The displacement of voltage Vo1 is then very easily generated in a standard difference amplifier.

A differentiator circuit is used to provide a direct velocity, output Vo1.

Transmitter

The discussion of the receiver assumed equal input intensities to the sensor; the transmitter equalizing loop uses feedback to equalize those intensities. It also takes the levelling loop error signal and alters the absolute level of the LED intensities to force the sum of the two (equal) intensities to be constant.

The equalizing loop samples the light from both LEDs via the dichroic mirror (these are the leakage paths). The Dm demultiplexer generates two quasi-continuous voltages: any difference in these voltages alters the drive to LED Lλ1. This loop operates independently of the levelling loop which drives LED Lλ2. Thus if the intensity of Lλ2 varies either as a result of ageing, or under control of the levelling loop, then the equalizing loop forces Lλ1 output to track Lλ2 variations.

MECHANICAL DESIGN

In addition to the design of the active element, the optical system and the electronics, some mechanical design had to be completed to mount the component parts. Care had to be taken, in this area, so that no spurious mechanical resonances were introduced into the system. Other aspects included the ability to perform optical adjustments in the x, y and z axes.

As shown in Figure 1, the leaf is completely immersed in water but the optical sensor is in an air filled section of the instrument. Whilst this is not a prerequisite of the design, it was felt that it represented an appropriate solution for the prototype where ease of access was a priority. The air compartment is formed using a sliding perspex cylindrical shield which closes onto O-ring seals in grooves cut around the circumference of the middle and bottom support plates.

So that the optical sensor measures the desired displacement due to the incident acoustic wavefield, the mounting for the leaf must be rigidly attached to the optical sensor assembly. This was achieved in the prototype by having two support plates; one with the leaf attached and the other supporting the optical sensor. These were separated by three pillars.

A further constraint on the support plates and pillars was that their dimensions must be small compared with the acoustic wavelengths of interest to avoid perturbing the incident acoustic wavefield. Furthermore, the vertical pillars had to be positioned sufficiently far away from the leaf not to influence the movement of the water. The support plates have also been used to mount the fibre optic couplers.

DISCUSSION

Current optical hydrophones are based on coherent or incoherent optical techniques. Hydrophones such as this prototype instrument have a number of practical advantages over their coherent cousins. They do not require coherent sources (lasers) or small single mode fibres (Tietjen, 1981). Furthermore their output is simply intensity rather than phase or frequency modulated.

The sensitivity of the instrument is limited by the optical and electronic system noise. The theoretical noise equivalent displacement is 1.4×10^{-11} $m/\sqrt{Hz}$, which corresponds to a sound pressure spectrum level of 102dB re

$1\mu Pa/\sqrt{Hz}$ at 1kHz. An order of magnitude improvement is expected to be achieved by installing more sensitive avalanche photo diodes in the optical detector.

The performance of this system is state of the art for an intensity modulated system but is below that for interforemetric (coherent) instruments. One of the major advantages of this device is its increased sensitivity at low frequencies compared to conventional hydrophones. As it stands, our system is predicted to be able to detect spectral levels of 62dB rel $\mu Pa/\sqrt{Hz}$ at 10Hz, which is below ambient noise.

Experimental confirmation of the instrument's predicted performance both in terms of the minimum detectable displacement and its frequency response will be provided during its evaluation in a test tank.

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REFERENCES

[1] R.D. Blevins, 'Flow-induced vibration', Robert E. Krieger Publishing Co. Inc., (1986).

[2] Sir Horace Lamb, 'Hydrodynamics', Cambridge University Press, (1975).

[3] B.W. Tietjen, 'The optical grating hydrophone', J. Acoust. Soc. Am., vol. 69, No. 4, (1981).

Figure 1 Schematic of prototype instrument showing optical sensing head and active element configuration.

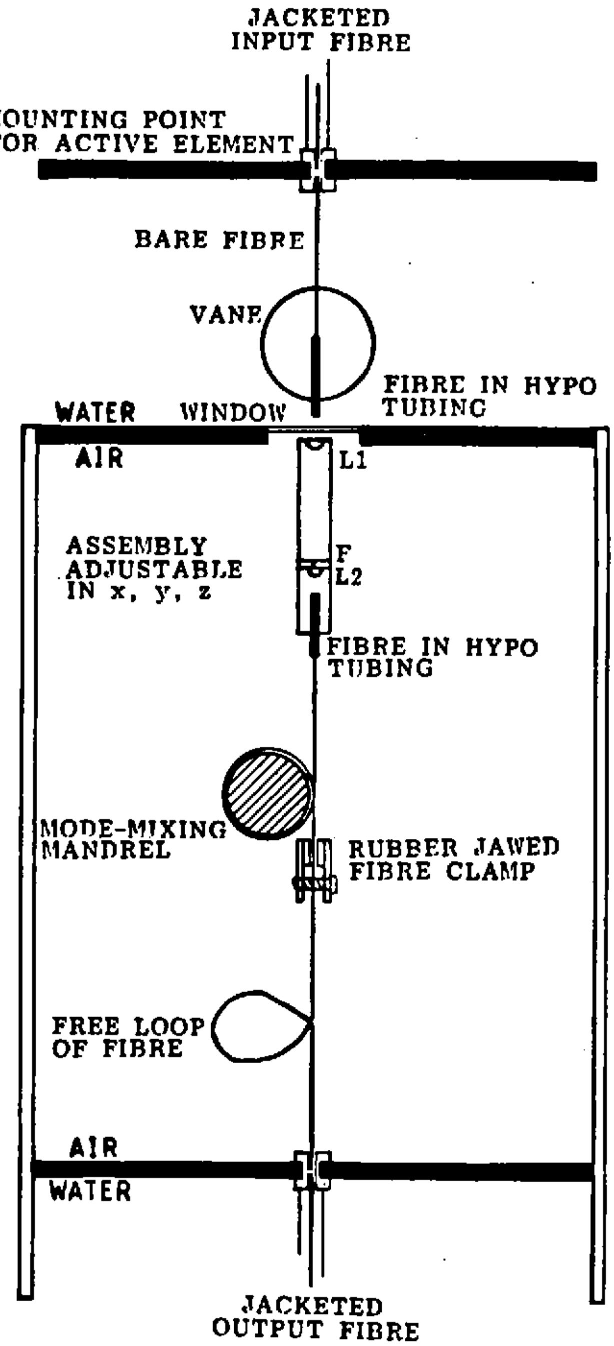

Figure 2 Schematic of electronic system.
S denotes the synchronizing signal derived from the master clock.