THE USE OF A LASER HYDROPHONE AS A MEANS OF ACOUSTIC CALIBRATION

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1. INTRODUCTION

A laser hydrophone is an optical interferometer in which the light from a laser is split into two beams that travel along different optical paths before being recombined on a photodetector. Since the two beams are coherent, the intensity of the optical signal formed when they recombine is a function of the phase difference between them. If the optical path length travelled by one (or both) of the beams is modulated by the acoustic signal there will be a variation of the phase difference between the two recombining beams. This leads to a modulation of the detected light, from which the acoustic intensity and frequency can be measured.

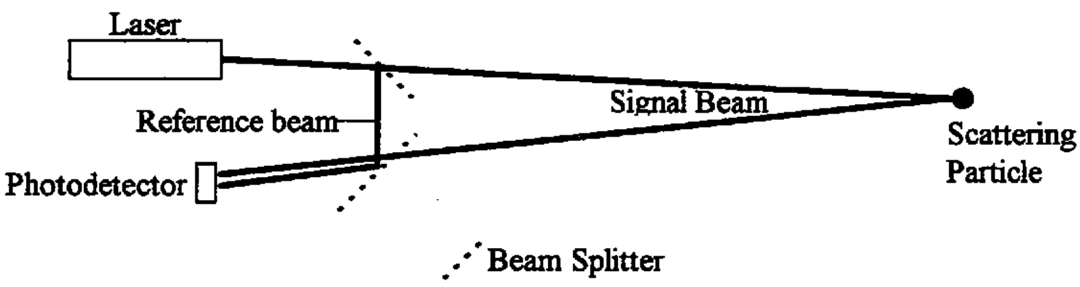
The optical path difference travelled by the laser beams can be modulated by two different effects. In the presence of an acoustic field small particles suspended in the water vibrate with the same amplitude and frequency as the water molecules. If the beams are scattered from these vibrating particles the physical distance travelled by the beams is modulated. The other effect is that the change in pressure in the acoustic wave modulates the refractive index of the water due to the acousto-optic effect, and so light that travels through the region of varying refractive index experiences a phase modulation. Which of the two causes of modulation is dominant depends on the optical arrangement and acoustic frequency.

Although we have not yet used the laser hydrophone as a means of acoustic calibration, it offers a number of potential advantages over existing methods. This paper describes the principles of the technique and the advantages that it offers.

2. OPTICAL ARRANGEMENTS

There are basically two different optical arrangements for a laser hydrophone which are known as the dual beam and reference beam arrangements. In the reference beam arrangement (figure 1) only one beam (the signal beam) travels though the water and it is scattered back to near its launch optics where it interferes with a reference beam which has travelled along a fixed path. In most systems the scattered light that is detected travels exactly antiparallel to the original beam, however for the sake of clarity this diagram shows a system in which the outward and return paths are slightly divergent. The scattering can occur off either a solid object or from particles suspended in the water. If particle scattering is used the laser beam is focused to a waist at some position in the water, and most of the light detected originates from the region around the waist.

Figure 1. Schematic diagram of reference beam arrangement



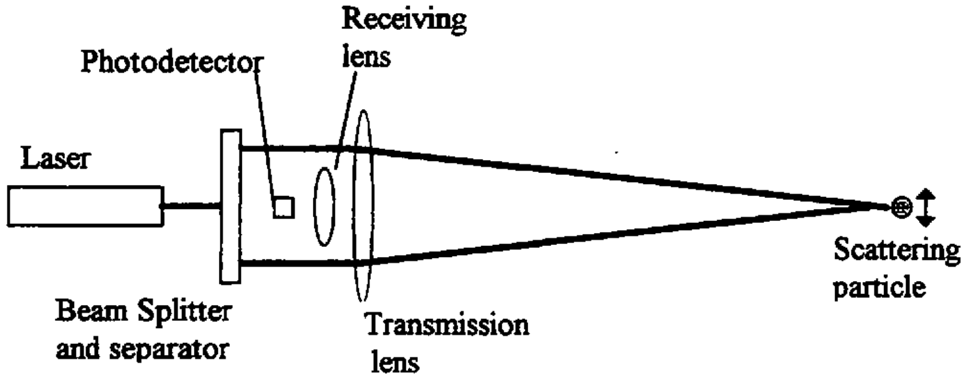
Particle vibration only has an effect if it modulates the distance travelled by the laser beams. For the reference beam arrangement the phase modulation of the signal beam for a given particle vibration is largest if the vibration is parallel to direction of the beam. For other angles of vibration the phase modulation induced is reduced by the cosine of the angle between the direction of the vibration and that of laser beam, and so the hydrophone has a directional response.

The modulation induced by the acousto-optic effect is proportional to the mean change in refractive index along the path of the signal beam which is determined by the integrated acoustic pressure. As well as the pressure magnitude this will depend on the acoustic frequency and propagation direction. The greatest response occurs if the acoustic wave is travelling perpendicular to the laser beam as in this case the pressure variation will be in phase at all points along the beam.

If the light is reflected off a fixed object then only the acousto-optic modulation will be observed, Jia *et al* [1]. It is also possible to reflect the light off of a compliant membrane in the water designed to vibrate at the same amplitude as the water molecules, in which case both types of modulation are involved.

In a dual beam arrangement (figure 2) both beams travel through the water and are focused, by the transmission lens, so that their waists are at the position where they cross. The receiving optics are designed so that only light scattered by particles in the region where the two beams cross is focused onto the photodetector. For this arrangement a vibrating particle will give the greatest modulation if it is vibrating in the direction shown in figure 2. For other vibration directions the modulation produced falls off as the cosine of the angle between the actual and optimum direction.

Figure 2. Schematic diagram of reference beam arrangement



The modulation produced by the acousto-optic effect for the dual beam arrangement is determined by the difference in the pressure integrated along the two laser beams to the scattering particle. Although somewhat complicated, it is possible to calculate the modulation that would be obtained for a given amplitude and frequency of any form of acoustic wave. Because the modulation is dependent on the difference between the integrated pressures along the two laser beams, it can be strongly dependent on the form of the acoustic wave. For the reference beam arrangement the modulation is less dependent on the waveform as it is determined by the integrated pressure along a single beam.

The amplitude of particle vibration for a given pressure is inversely proportional to the frequency. Therefore the phase modulation due to particle motion falls off at higher frequency, while that due to the acousto-optic effect, which depends on the pressure itself, remains constant. As the acousto-optic effect is an integrated effect over the distance travelled by the laser beams through the water the modulation due to it will increase for longer paths. Therefore the particle vibration will tend to dominate at lower frequencies and shorter path lengths, while the acousto-optic effect will do so at higher frequencies and longer path lengths, Crickmore and Coltmann [2].

3. ADVANTAGES OF LASER HYDROPHONE

The laser hydrophone has a number of advantages over conventional hydrophones including its non-invasive nature, small sampling volume, automatic calibration and known direction response.

A major advantage is that the technique is non-invasive and so there is no need to place a physical object in the water. For acoustic calibrations this has the advantage that the sound field is not disturbed by placing a hydrophone in to measure it. The non-invasive nature may also prove useful in other situations such as measuring sound in a hostile environment where a conventional hydrophone is likely to be damaged. There is however the need to have optical access to the sound field and for particles in the water to scatter the light. Most samples of water, including normal tap water, have sufficient particles so this does not generally present a problem unless the water has been very carefully filtered to remove them.

For measurements made using the particle vibration as a source of modulation the measuring volume is determined by the optical arrangement and can be made very small. Both the reference and dual beam arrangements have measurement volumes in which one dimension is much longer than the other two. The dual beam arrangement gives the better defined measurement volume which for circular laser beams is an ellipsoid; volumes as small as 70μm diameter by 700μm long are easily achievable. In contrast to conventional hydrophones a reduction in the measurement volume of the laser hydrophone does not necessarily result in a reduction of its sensitivity.

Another useful feature of the laser hydrophone is that there should be no need to calibrate it. This is because the system actually measures the varying phase difference induced between the two beams, and from the details of the optical system and knowledge of the dominant modulation method the acoustic intensity can be calculated. If a system is designed to measure the acousto-optic effect this phase modulation is directly related to the integrated acoustic pressure along the laser beam(s), via the known value of the acousto-optic coefficient for water. For measurements utilising the particle vibration, the amplitude of the component of this vibration in the direction to which the optical arrangement is sensitive can be calculated directly from the phase modulation.

As explained in section 2 the amplitude of the modulation caused by particle motion is dependent on the vibration direction and so the hydrophone is inherently directional, and remains so even at low frequencies when the acoustic wavelength is much greater than the measurement volume. This means that the laser hydrophone should be very useful in making calibrated directional measurements of an acoustic field. The direction in which the hydrophone is most sensitive is easily changed by rotating the system about its optical axis.

Depending on how the optical signal is processed, the laser hydrophone makes a direct measurement of either the amplitude of the particle vibration or its velocity as function of time. Therefore it should be very useful in the calibration of other types of acoustic velocity sensors as the velocity, in a given direction, can be obtained directly rather than having to deduce it from a set of pressure measurements made at closely spaced points.

4. EXPERIMENTAL RESULTS

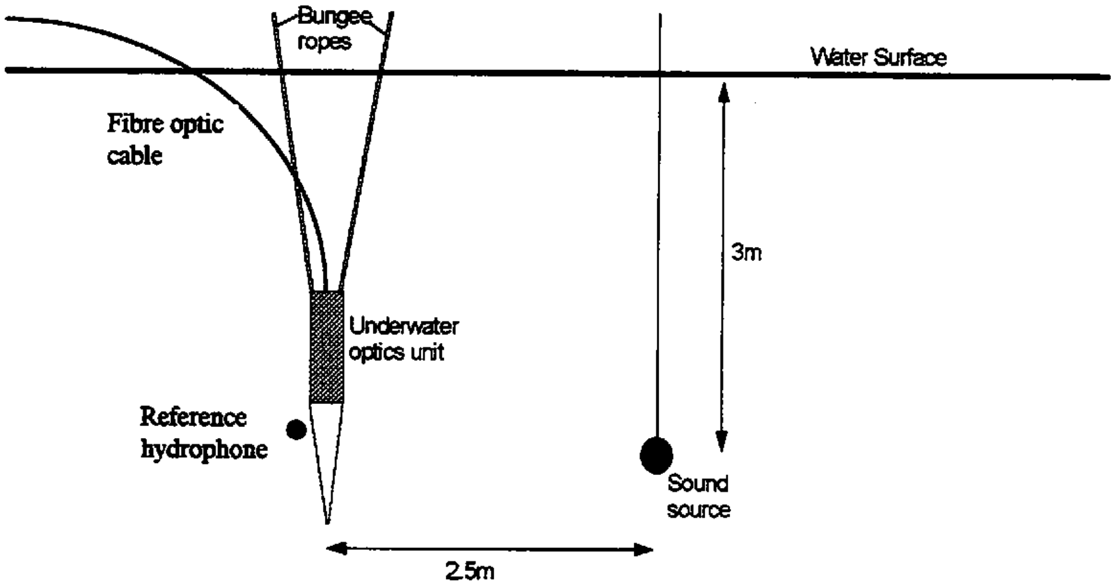
Two sets of measurements using a dual beam arrangement have been carried to demonstrate the operation of this technique. In the first set measurements were made in a sound tube which consisted of a column of water 50 cm deep contained within a thick walled steel tube, Crickmore [3]. A loud speaker located at the bottom of the tube was used to generate sound. The light entered and exited the tube through a glass window in its side. Measurements were made at frequencies up to 800 Hz. The low frequencies and the fact that the laser beams only travelled a few cm through the water, meant that the optical modulation was dominated by the particle vibration. The pressures associated with these velocities were estimated by making the rather crude assumption that a simple standing wave was set up in the tube by the reflection of the acoustic wave at the free surface of the water. The pressures obtained were with within a factor of two of those measured with a reference hydrophone located just above the laser measurement volume. The differences are thought to be mainly due to the fact that the acoustic wave in the sound tube was not exactly a simple standing wave.

The minimum amplitude of vibration that could be measured was 4nm and was limited by the low level of scattered light returning to the photodetector. The detected light was typically only a few nW as compared to the 40mW of laser power transmitted into the sound tube.

The second set of experiments was designed to demonstrate modulation caused by the acousto-optic effect. The laser itself remained in a laboratory while its output was split into two beams which were coupled into fibre optic cables. The cables then transmitted the light to a waterproof optics unit that was suspended by elastic ropes in a large tank of water (figure 3). The optics unit formed a beam from the output of each fibre which then propagated 50cm through the water before crossing. Light scattered by particles in the tank was focused by a receiving lens into an optical fibre that transmitted it back to the laboratory. A reference hydrophone was located near to the laser hydrophone to provide an independent measure of the acoustic pressure.

This system operated most reliably at frequencies in the range 12-20kHz when the pressure measured by the laser hydrophone was within 25% (1 dB) of the pressure that was measured by the reference hydrophone. Exact agreement was not expected as the reference hydrophone makes essentially a point measurement while the laser hydrophone measures the pressure over a length of 50 cm. The minimum pressure that could be detected was 60Pa, again limited by the low level of scattered light. Lower pressure levels could be detected by using a higher power laser, a lower noise detector or seeding the tank with particles that scatter more light. For experiments in which the light is scattered off a solid object, much more optical power will be received by the photodetector and so measurements of considerably lower pressures will be possible.

Figure 3. Experiment to demonstrate acousto-optic modulation



5. ACCURACY OF MEASUREMENTS

For measurements made when the acousto-optic effect is dominant the major source of error will be the accuracy with which the phase modulation of the optical signal can be determined. In the experiments that we have carried out so far no detailed study has been made of this. Some estimate can be made from measurements during the second set of experiments in which the frequency was 12 kHz and the acoustic pressure, as measured by the reference hydrophone, was varied between 100 and 1000 Pa. If the phase modulation is plotted against pressure the best straight line that can be drawn through the points does not deviate by more than 9% (=0.37dB) from any point. This demonstrates that at least this accuracy can be obtained and it is probable that a much better figure is possible.

For measurements in which particle vibration dominates there is an additional uncertainly as to how well the particles follow the acoustic motion. It has been shown that smaller particles at lower frequencies exactly follow the acoustic motion, but if the particle size or frequency is increased the vibration amplitude falls to $1/s$ of the acoustic motion where s is the relative density of the particles, Vignola [4]. In an experimental system this problem can be overcome by seeding the water with neutrally buoyant particles which will follow the acoustic motion exactly at all frequencies. It is also possible to obtain such particles with a metal coating which gives the advantage of a much greater level of scattered light thereby improving the signal to noise of the system.

The laser technique has been used elsewhere for calibrations of microphones in air when it was found that measurements could be made with an accuracy of ± 0.03 dB, Taylor [5]. The sensitivity of the microphones measured using this method were in agreement with those made using a reciprocity technique. Due to its much lower acoustic impedance, particle velocities in air tend to be higher than those in water, which may make accurate measurement somewhat easier.

6. CONCLUSIONS

The laser hydrophone offers a number of advantages over conventional calibration systems including:

No need to place a physical object in the sound field to disturb the flow.
The ability to make either particle vibration measurements in a very small volume or integrated pressure measurements over a long distance.
A directional response even with a very small sampling volume.
No requirement to calibrate the system against an external reference.
Direct measurement of vibration amplitude or velocity.

The ability of the laser hydrophone to make both velocity and pressure measurements has been demonstrated experimentally.

7. REFERENCES

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