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THE OPTICAL MICROPHONE-FACT OR FICTION

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1. INTRODUCTION

This paper describes various techniques by which the displacement of a microphone diaphragm may be measured optically. The need for a non-electrical method of measurement came about as a result of previous research into a force-feedback microphone. In this microphone the electrodes (one on each side of the diaphragm) were used to carry the feedback signal. The normal technique of DC excitation which generates a change in voltage from the change in capacitance could not therefore be employed. In the prototype force-feedback capsule the change in capacitance was used to modulate the frequency of an oscillator and this FM signal was then frequency shifted and demodulated. Unfortunately the feedback signal was found to affect the frequency of the oscillator directly, forming an unwanted high-frequency feedback path that proved difficult to stabilise. In addition to this the demodulator was found to introduce excessive phase lag at high frequencies which limited the amount of attainable feedback. The closed-loop frequency response was however excellent and so alternative methods of measuring the diaphragm displacement were considered.

2. OPTICAL-FIBRE SENSORS

2.1 Single-fibre Sensor

A block diagram of a single-fibre system is shown in figure 1. Light from the source is passed along an optical fibre to a splitter. The purpose of the splitter is to couple light from the source to the output fibre and light from the output fibre to the sensor. Ideally there is no light coupled directly from the source to the sensor. Light from the output fibre falls on the diaphragm which has a mirrored surface and thus reflects the light back onto the output fibre. Figure 2 shows the effect of three different fibre-to-diaphragm separations. The amount of light passed back down the output fibre varies as the inverse square of the separation.

2.2 Two-fibre Sensor

Figure 3 shows the block diagram of a two-fibre system. In this system separate fibres are used to carry the light from the source and the reflected light back to the sensor. Figure 4 again shows the effect of three different fibre-to-diaphragm separations. At zero separation no light is coupled from one fibre to the other, but as the separation is increased more light is coupled until a maximum is reached. This is shown as the centre position of the three given in figure 4. At greater separations the amount of light coupled falls, eventually following the inverse square law. An improvement to this system is to shape the ends of the fibres to refract as much light as possible from one fibre, via the diaphragm, to the other. A graph showing the percentage of transmitted light received at the source vs separation is shown in figure 5. It can be seen that the greatest response is achieved with the two-fibre sensor with shaped ends. This system was thus analysed to see if it was sensitive enough for microphone use.

2.3 Noise Analysis

The major source of noise in the system is the shot noise in the photo-diode due to the steady bias current flowing. This noise is proportional to the square-root of the photo-diode current and the noise thus increases with increasing light. The response curve is such, however, that the response initially increases faster than the noise. There is clearly then a bias point at which the signal-to-noise ratio is optimal. This bias point was determined and the effective self-noise of the microphone was calculated at this point. The displacement of the diapragm at 0dB SPL was that of a CALREC Soundfield Microphone capsule and it should be noted that although this figure is very small it is not untypical. The calculation is shown in figure 6. The unweighted self-noise in a bandwidth of 20 kHz was found to be about 70 dB SPL and this was approximately verified by experiment. This figure is very much higher than would be acceptable, indeed in practical tests the human voice was only audible above the noise if the speaker was very close to the microphone!

2.4 Methods of Improving the Signal-to-Noise Ratio

As with any transducer the most obvious way of increasing the signal-to-noise ratio is to increase the excitation. The infra-red led used in calculation of self-noise was a commonly available type which coupled a power of 0.5 mW into the 1 mm fibre used. Recently introduced leds of the surface emitting type can now produce up to 20 mW but as the noise increases with the square-root of excitation this only gives an improvement of 16 dB.

Another way in which the response may be increased is to reduce the diameter of the fibre. This technique would work were it not for the fact that the led does not couple light effectively into narrow fibres, thus any potential increase in reponse is counteracted by an effective decrease in excitation. A source which is capable of coupling large powers into narrow fibres is the laser led. This however produces coherent light and interference effects then become a problem. The investigation into optical-fibre sensors was terminated at this point as it was decided that the improvement required was unachievable.

3. INTERFERENCE SENSORS

3.1 The Michelson Interferometer

During the search for high-power optical sources it was discovered that laser led and lens packages were available which gave coherent beams of low divergence. These packages were of small physical size and were thus suitable for use within a microphone housing. Most interference measuring techniques use fringe counting to allow measurement of distances greater than one wavelength, but sub-wavelength measurement is possible although the response is non-linear. The most well known interferometer is the Michelson and a block diagram of this is shown in figure 7. The beam of coherent light from the laser passes though a beam splitter to the two mirrors. The reflected beams recombine at the beam splitter and pass to the photo-diode. The difference in path lengths determines whether the beams combine constructively giving a high intensity beam, or destructively giving a low intensity beam. The variation in intensity vs path length difference is sinusoidal and is shown in figure 9 (Line with diamonds). Given that the wavelength of the light from commonly available laser leds is about 600 nm it can be seen that the response is very much higher than the optical-fibre sensors. Disadvantages of the Michelson interferometer are that it is difficult to align and that it is sensitive to movement of either mirror.

3.2 The Fabry-Perot Interferometer

The Fabry-Perot interferometer is a multiple-beam type, a block diagram of which is given in figure 8. The beam splitter in this case allows us to measure the reflected light from the cell, but also gives a measure of the light output from the laser. This is available at the upper of the two photo-diodes and allows the output of the laser to be stabilised by negative-feedback. The interference takes place between the multiple reflections of the beam between the two mirrors of the Fabry-Perot cell. The first mirror is partially reflective so as to allow light in and out of the cell. It has been determined that if the reflectivity of the first mirror is made to be 1/3 then the response is as shown in figure 9 (Line with crosses). For any other value of reflectivity the response does not reach zero. Although this interferometer has a lower response than the Michelson type it has regions in its response which are much more linear. This is demonstrated by the graph of the slopes of the responses of the two types which are shown in figure 10 (Line types as figure 9). The Fabry-Perot interferometer has the advantage that it is only sensitive to changes in the separation of the two mirrors, and that alignment consists of ensuring the two mirrors are parallel.

3.3 Noise Analysis

The noise sources in the interference type of sensor are identical to those in the optical-fibre sensor. The same set of equations is therefore used with differing values of response and standing power, and these are given in figure 11. The self-noise, again unweighted in 20 kHz, is approximately 11 dB SPL. This figure was calculated for a laser power of 2 mW which is typical of commonly available laser leds. The calculations given in figures 6 and 11 assume that the shot noise in the photo-diode is the dominant source of noise. This is not in fact the case as any noise in the source will contribute just as much to the final noise figure as noise in the sensor. If the Fabry-Perot interferometer is used,the source output may be stabilised by feedback. Assuming the loop gain to be high the noise in the source will be dictated by the noise in the feedback path i.e. the photo-diode. This will produce as much shot noise as the sensor photo-diode and so our overall noise figure will be worsened by 3 dB. The calculations, however, give us the unweighted noise figure and the more commonly used A-weighted value would be about 5 dB lower. The final value for the self-noise of the system is thus 9 dB A-weighted which compares favourably with existing electrically excited systems.

3.4 Disadvantages
Figure 10 shows that the system is only capable of measuring diaphragm excursions up to about 1/3 wavelength or 200 nm and even at lower displacements the linearity is very poor. The maximum signal this system could handle is therefore only about 105 dB SPL which is unacceptably low and the distortion, even for modest SPLs, would be unacceptably high.

4. FORCE-FEEDBACK

A full description of the effects of force-feedback as applied to microphones is given in Keating [1] but to summarise:
The distortion is reduced by the value of the loop-gain.
The headroom is increased by the same value.
The frequency response is made independent of the effects of diaphragm resonances.
The diaphragm mechanical damping may be reduced giving a potential reduction in noise.

5. CONCLUSIONS

The information given in the previous sections shows that if an optical microphone using the Fabry-Perot interferometer is constructed, and that it is controlled by force-feedback with a loop gain of 40 dB or more, then the resulting microphone system would be superior to existing types in many respects. The major exception is that the optical force-feedback microphone would be of much greater complexity. It would thus find applications in measurement and indeed the original aim of the research was to produce a measuring version of the soundfield microphone. With the advent of integrated optics and cheap electronics, however, the optical force-feedback microphone may one day become commonplace.

6. REFERENCES

[1] D A KEATING, 'Force Feedback Microphone', Proc. I.O.A., Vol. 8 part 6, Nov 1986 pp. 67-73.

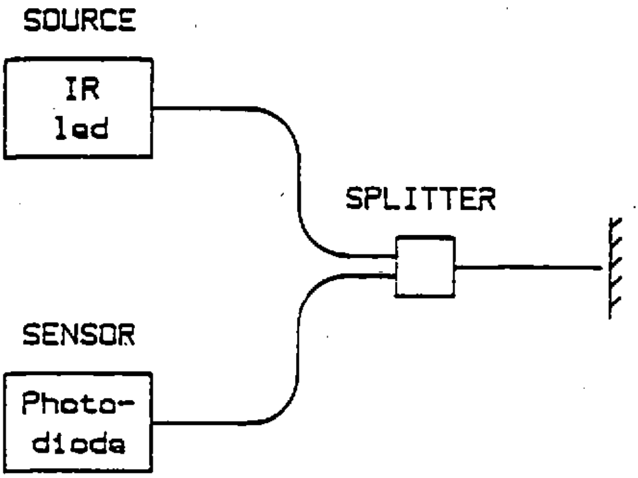


Figure 1. Block diagram of single-fibre sensor

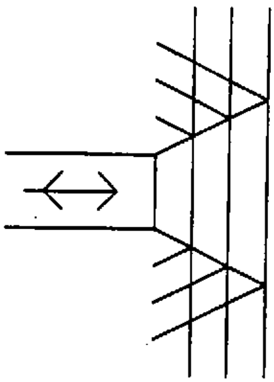


Figure 2. Action of single-fibre sensor

OPTICAL MICROPHONE

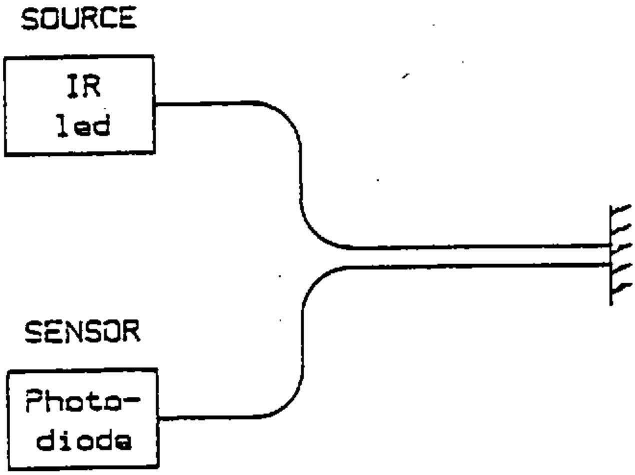


Figure 3. Block diagram of two-fibre sensor

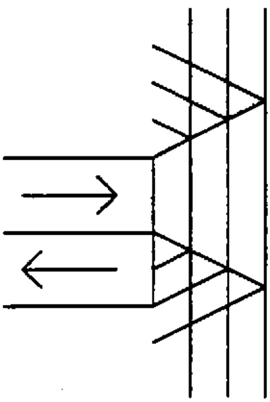


Figure 4. Action of two-fibre sensor

OPTICAL MICROPHONE

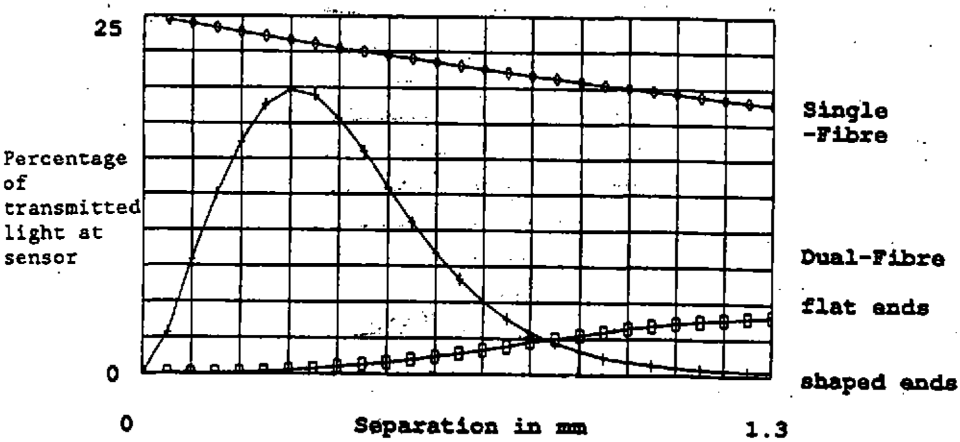


Figure 5. Graph showing responses of optical-fibre sensors

electron charge	$e := 1.6 \cdot 10^{-19}$ c
bandwidth	$B := 20 \cdot 10^{3}$ Hz
sensor responsivity	$s := 0.4$ W/m
photo-diode responsivity	$d := 0.5$ A/W
standing or bias power	$p := 15 \cdot 10^{-6}$ W
displacement at 0dB SPL	$ref := 3 \cdot 10^{-13}$ m rms
overall responsivity	$r := s \cdot d$
	$r = 0.2$ A/m
standing current	$i := p \cdot d$
	$i = 7.5 \cdot 10^{-6}$ A
noise current	$in := \sqrt{2 \cdot e \cdot B \cdot i}$
	$in = 2.191 \cdot 10^{-10}$ A rms
noise displacement	$dn := \frac{in}{r}$
	$dn = 1.095 \cdot 10^{-9}$ m rms
self noise	$ns := 20 \cdot \log\left[\frac{dn}{ref}\right]$
	$ns = 71.249$ dB SPL

Figure 6. Self-noise calculation for optical-fibre sensor

OPTICAL MICROPHONE

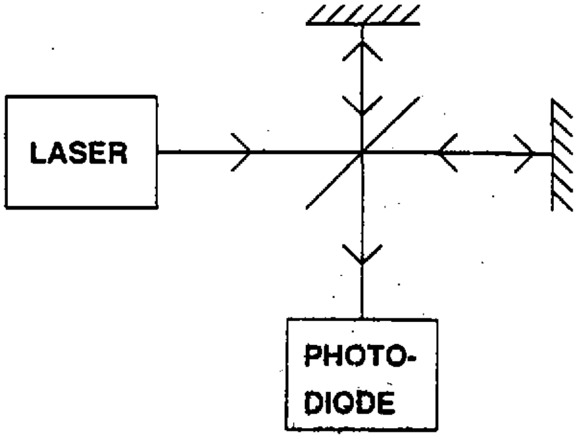


Figure 7. Block diagram of Michelson interferometer

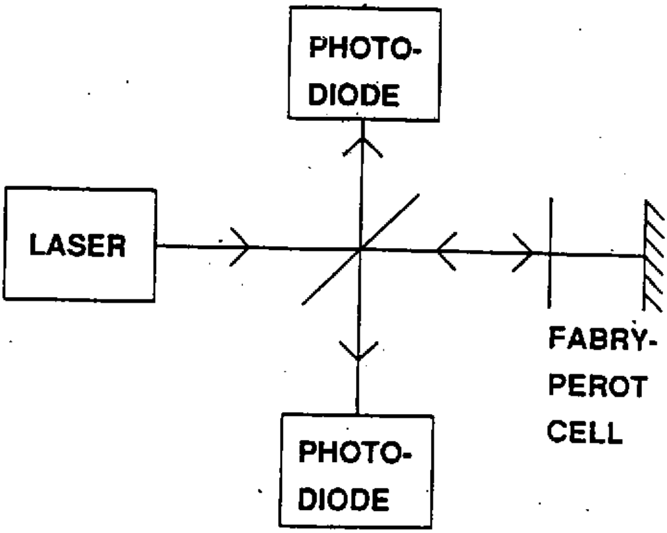
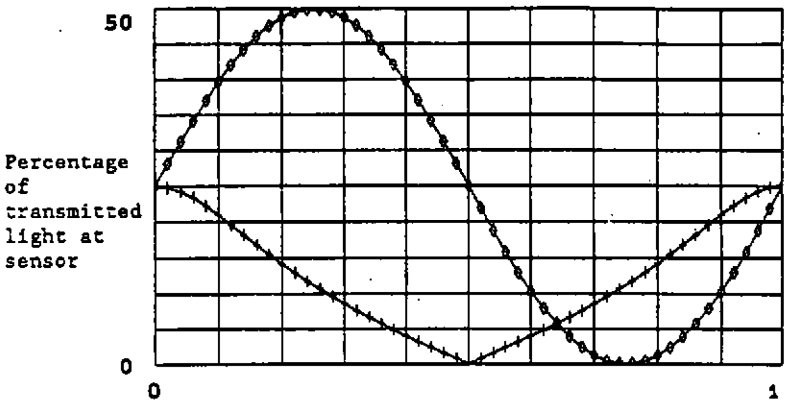
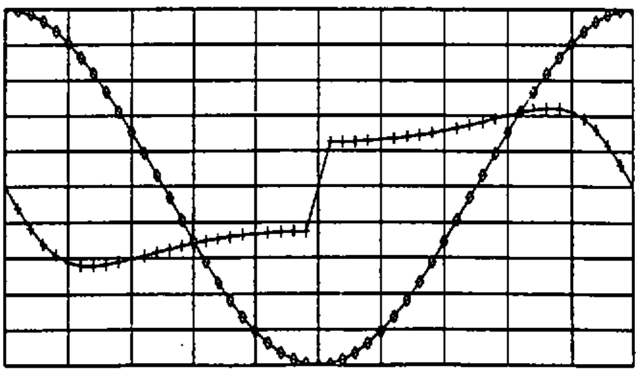


Figure 8. Block diagram of Fabry-Perot interferometer



Path length difference from 0-1 wavelength

Figure 9. Graph showing responses of interference sensors



Path length difference from 0-1 wavelength

Figure 10. Graph showing slopes of responses of interference sensors

OPTICAL MICROPHONE

electron charge	$e := 1.6 \cdot 10^{-19}$ c
bandwidth	$B := 20 \cdot 10^{3}$ Hz
sensor responsivity	$s := 1.67 \cdot 10^{3}$ W/m
photo-diode responsivity	$d := 0.5$ A/W
standing or bias power	$p := 2.5 \cdot 10^{-4}$ W
displacement at 0dB SPL	$ref := 3 \cdot 10^{-13}$ m rms
overall responsivity	$r := s \cdot d$
	$r = 835$ A/m
standing current	$i := p \cdot d$
	$i = 1.25 \cdot 10^{-4}$ A
noise current	$in := \sqrt{2 \cdot e \cdot B \cdot i}$
	$in = 8.944 \cdot 10^{-10}$ A rms
noise displacement	$dn := \frac{in}{r}$
	$dn = 1.071 \cdot 10^{-12}$ m rms
self noise	$ns := 20 \cdot \log\left[\frac{dn}{ref}\right]$
	$ns = 11.055$ dB SPL

Figure 11. Self-noise calculation for Fabry-Perot sensor.