A MINIATURE OPTICAL ACOUSTIC EMISSION TRANSDUCER

D.C. Emmony, M.W. Godfrey and R.G. White

Department of Physics
Loughborough University of Technology
Loughborough, Leicestershire LE11 3TU
United Kingdom

ABSTRACT

The optical transduction of acoustic emission signals offers many advantages over piezoelectric devices. These include high bandwidth, no modification to the signal as well as providing contactless measurement. The major difficulties associated with optical devices are stability against low frequency vibrations and the generally complex nature of an optical interferometer. This paper describes the attempts to miniaturize a Michelson interferometer while at the same time overcoming some of the stability problems associated with these devices.

Active stability of an interferometric transducer with dimensions of \( \sim 5 \text{cm} \) (2" ) cube has been achieved over 8 fringes of red light at 100Hz and 4 fringes at 300Hz. The range of active stabilization of the interferometer is limited by the frequency response of the large amplitude piezoelectric element and the filter characteristics of the feedback electronics. A sensitivity of \( 0.5 \text{V} (0.5 \times 10^{-10} \text{m}) \) has been achieved.

INTRODUCTION

The ideal acoustic emission transducer will possess a number of characteristics. It will not need to be contacted to the surface being investigated and therefore will not load the surface in any way. Consequently the signal being measured will be unchanged. Because the optical sensing beam is massless it is theoretically capable of a very wide bandwidth. Light can be focussed and therefore the area of the surface being investigated can be very small. Conventional piezoelectric transducers do not fullfill
the above criteria but they are very sensitive. Capacitative transducers can be made to have a high sensitivity but at the expense of large interaction area and a requirement for a high degree of finish on the structure surface.

Several authors\(^1,2\) have investigated the use of optical interferometry to measure small high frequency displacements such as those associated with acoustic emission events. The interferometers tend to be relatively large instruments requiring substantial mechanical stability and are therefore rather unsuited to most practical experimental environments.

A microscope interferometer has been modified using a cantilever driven reference mirror to allow active stabilization of the instrument against low frequency vibrations. This has advantages over a thickness mode piezoelectric reference in that the excursions of the reference mirror can be several wavelengths for the application of relatively low voltages. However, optimisation of the stabilization must be a careful trade-off between bandwidth and the range of stabilization.

INTERFEROMETRY DESIGN

The principle of operation of an optical interferometer is well known. Briefly the optical path difference (OPD) between a sensing beam and a reference beam varies as shown in fig. 1. When the OPD is zero or an integer number of wavelengths the two beams constructively interfere leading to a maximum signal on a photodetector (A). When the OPD is given by \((n+\frac{1}{2})\lambda\) where \(\lambda\) is the light wavelength, then the photodetector signal is zero (B). It can be seen that the sensitivity of the interferometer is given by \(\frac{dI}{dx}\) and this is a maximum when the OPD is an odd number of \(\lambda/4\) at C. Therefore to maintain maximum sensitivity the reference mirror must be adjusted and maintained to satisfy this last criterion. This is known as optical stabilization and is normally carried out by means of some active element in the reference beam together with feedback to maintain the mid-fringe position near C. The sensitivity is not a

![Figure 1.](image-url)
strongly varying function around C. A 20% excursion from C only results in a 2% change in calibration.

Palmer and Green\(^1\) have used the Mirau or Fizeau in-line interferometer as well as the Michelson. In the former the reference mirror is on or near the focusing lens which leads to a compact design which is particularly insensitive to axial bending, but in any attempt at miniaturization the position of the reference mirror is rather inaccessible. In the Michelson interferometer the reference mirror is parallel to the axis of the instrument as in fig. 1. In order to compensate for low frequency vibrations the reference mirror must be capable of moving at the same speed as the subject mirror and the amplitude of the reference mirror must also be equal to that of the subject. Thickness mode ceramics typically have piezoelectric coefficients of \(\sim 10^{-6}\) mm V\(^{-1}\) with a corresponding 300 volts required for one complete fringe traversal. This is the lowest voltage acceptable if an over-under switch in the electronic circuitry is to be avoided with the associated dead time in these arrangements (Palmer and Green\(^1\)). In order to provide continuous access it was decided that the optical stabilizing system should be capable of compensation over several fringes and that this was best done using a reference mirror attached to a piezoelectric bimorph which acts as a cantilever.

Initially an optical bench interferometer was constructed for feasibility tests and then a surface finish interference microscope objective was adapted by the installation of a 3mm long piezoelectric bimorph element with a 1mm diameter aluminised mylar mirror at the free end. The characteristics of the bimorph are such that the amplitude is 1µm with the application of 150 volts.

A full account of the stabilization and cantilever properties will be given elsewhere. The interference objective is based on a Michelson interferometer with the beam splitter cube arranged to lie just above the normal specimen surface (fig. 2). In its unmodified state the objective may be used with white light, that is the reference arm exactly matches the distance to the focus. The reference mirror mount was removed and replaced by the cantilever mirror and its associated power supply leads.

A 2mW HeNe laser was coupled to the interferometer by a rigid rectangular box containing a \(\times 10\) microscope objective and a 50% reflecting beam splitter. The optical system is shown diagrammatically in fig. 3. The single transverse mode HeNe laser has a beam diameter of \(\sim 1\) mm and the \(\times 10\) objective spreads this beam to fill the interference objective. The laser radiation traverses the interferometer and returns to the beam splitter where half of the laser energy is deflected to the silicon photodiode. This simple photodetector is used to detect high frequency oscillations as in acoustic emission and also acts as the sensor in the optical
stabilization feedback loop. Only 12.5% of the HeNe laser beam is returned to the photodiode.

CHARACTERISTICS OF THE TRANSDUCER

The performance of the transducer was assessed and amplitude calibration carried out using a cantilever target and a thickness
mode piezoelectric plate. The cantilever target which was essen-
tially of the same construction as the stabilising reference mirror
was driven by an r.f. oscillator at 50kHz and the amplitude was such
that more than one whole interference fringe was displayed on an
oscilloscope. This gave the photodetector output with displacement
and allowed the minimum displacement above the noise level to be
measured. This figure was then confirmed by using the thickness
mode ceramic at the same frequency but with a displacement amplitude
down to the noise level using the theoretical piezoelectric coeffi-
cient.

The minimum detectable displacement measured as described
above was 0.5Å. Calculations on shot noise for a Michelson inter-
ferometer employing a 2mW laser as a light source suggest this
figure is an order of magnitude too large3. The major contribution
to the degradation of the noise ratio was found to be loss of light
energy in the system due to unwanted reflections. In addition to
increasing the shot noise to signal ratio this also puts more
stringent requirements on amplifier noise levels. The system was
limited by amplifier noise; laser noise was not a problem.

The characteristics of the stabilization loop were also
determined. A long cantilever element and mirror acting as an
object surface was driven with an oscillator. The ability of the
stabilizing system to maintain the fringe mid-point as the amplitude
of the oscillations increased was noted as a function of frequency.
The system was able to maintain stability over 8 fringes at 100Hz
but only 2½ fringes at 500Hz. Using more elaborate electronic
filtering it should be possible to extend the 500Hz figure to 3½
fringes. The present stability range is the result of careful
optimisation of the bimorph length, the feedback filter points and
the total system gain.

CONCLUSION AND DISCUSSION

The prototype transducer described here uses a small inter-
ferometer but the whole instrument including laser light source
has dimensions 5 x 5 x 40cm. Several modifications can in principle
lead to a very compact overall instrument. It is stated above that
the optical system is very wasteful in laser light and the 12.5%
figure does not include reflection losses. The laser input/output
beamsplitter could be dispensed with by positioning the photodetec-
tor in the unused beam of the interferometer opposite the reference
mirror with an immediate improvement of light on the detector of
400%. Furthermore, the signal to noise ratio could be improved
with the use of a higher power laser.

The removal of the input/output beamsplitter would lead to a
shortening of the light source unit but the need to fill the micro-
scope objective aperture may still require a diverging lens.
Considerable reduction in size is feasible with a change in light source. The use of a semiconductor injection laser is an obvious choice although a move into the infrared may involve a reduction in sensitivity as well as difficulties in setting up the instrument.

In conclusion, it should be possible to increase the sensitivity to $0.05\lambda$ ($5 \times 10^{-12} m$) by adopting some of the above modifications and by making use of low noise detector/amplifier combinations.

ACKNOWLEDGEMENTS

This project was carried out with support from the Procurement Executive, Ministry of Defence. M.W.G. and R.G.W. acknowledge the support of SERC and University Research Studentships respectively.

REFERENCES

4. Vickers Instruments, York, United Kingdom.