REPORT

Future Transducer Technology Advances in Acoustics - a Strategy for the UK National Measurement System

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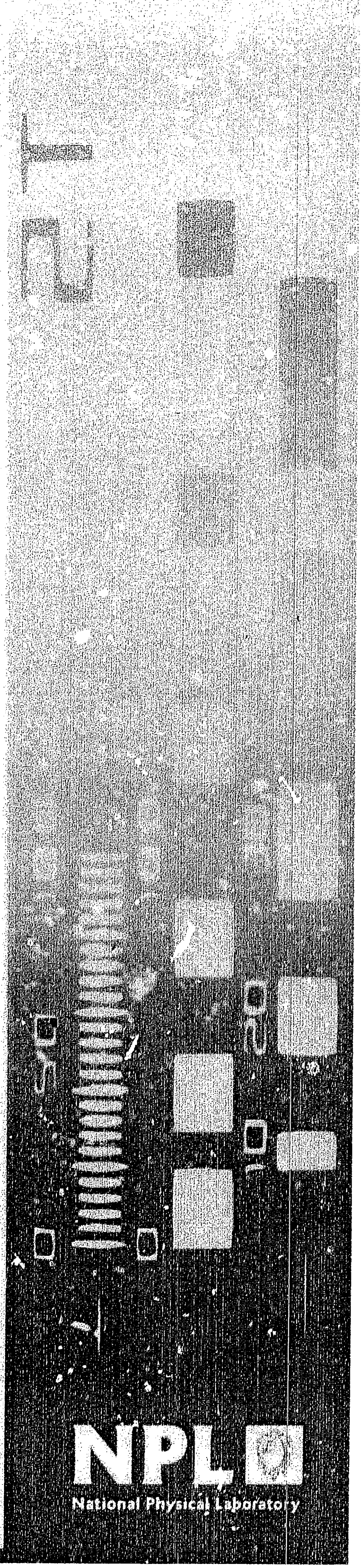

Future Transducer Technology Advances in Acoustics - a Strategy for the UK National Measurement System

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ABSTRACT

In the last decade several new technologies have emerged which could significantly change acoustical transducers and the range of measurements that can be made. New transducers could offer advantages to the UK National Measurement System (NMS) providing lower cost or more accurate metrology methods and calibrations but some could also present challenges if they were adopted in routine measuring instruments which required a traceable calibration.

This report reviews the technologies available and summarises the views of users and developers on the likely advances over the next decade. It then makes recommendations on a strategy to be adopted by the NMS particularly concerning: capacitive transducers for ultrasound in air, optical methods, micromachined acoustic transducers and force-feedback microphones.

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CONTENTS

1 INTRODUCTION

Acoustic metrology depends critically on the transducers available. In the last decade several new technologies have emerged which could significantly change acoustical transducers and even the range of measurements that can be made. New transducers could offer advantages to the National Measurement System providing lower cost or more accurate metrology methods and calibrations but some could also present challenges if they were adopted in routine measuring instruments which then required a traceable calibration. In order to determine how the National Measurement System should respond to these advances, a study was carried out to review the technologies, seek the views of users and developers on the likely advances and make recommendations on a strategy to be adopted.

1.1 BACKGROUND

Acoustical measurements in air and water cover a range of quantities (pressure, intensity, power...), a wide range of frequencies (1 Hz to 50 kHz in air and 10 Hz to 100 MHz in water), and a still wider range of levels (1 μPa to 600 Pa in air and 20 μPa to 200 MPa in water). A variety of transducers and calibration methods are required to cover these wide ranges.

1.1.1 Transducers for use in air

Transducers for the measurement of sound in air have changed little over the last 75 years. The principles described by Wente[1] in 1917 are still employed in modern measurement microphones[2] with minor improvements in materials and fabrication techniques. However, since the early 1980s engineers have been developing silicon chip microphones using the methods of semiconductor technology. Membranes of silicon as thin as a fraction of a micrometer can be etched from solid and used to provide the flexible diaphragm required for a microphone. Condenser microphones as small as 1 mm^2 with good sensitivity and a flat response up to 10 kHz can be obtained in this way. Micromachining methods can also be used to produce piezoelectric microphones in which the membrane contains piezoelectric elements that generate an output voltage when compressed. Other miniature microphones use piezoresistive elements to provide the sensor or use the sound pressure to modulate the output of a field-effect transistor directly.

These new designs could offer several advantages over conventional designs; their small size reduces the effect that they have on the field that they are measuring while the fabrication method allows them to be manufactured in bulk using the techniques of the semiconductor industry. In a recent foresight study[3], the utilisation of such microphones on acoustical instruments was ranked first for 'Potential for Exploitation' over all other topics in the Acoustics & Ionizing Radiation survey.

Other recent work[4] has led to the development of microphones whose properties can be controlled dynamically. These microphones have not been miniaturised yet but they could offer significant advantages in instruments which would change the properties of the microphone to match the measurement requirements as easily as present day instruments change the display.

1.1.2 Transducers for use in water

Transducers for the measurement of sound in water have been developed more recently than those for use in air and have therefore taken advantage of more modern materials and fabrication techniques.

Standard sources of sound in water at high frequencies have been mainly based on a wide range of piezoelectric materials from natural quartz to polycrystalline piezoceramics, whereas at low frequencies magnetostrictive devices are often used. The advantages of naturally occurring piezoelectric materials such as quartz are stability and reproducibility, whereas the low excitation voltages required for piezoceramics, and the wide range of materials now available, offer many advantages such as focusing or array configurations. More recently TERFENOL, a magnetostrictive material, with its high strain capability is finding increasing applications in low frequency high power applications.

The measurement of sound in water is based on the use of reference hydrophones, again mainly based on piezoelectric materials. At frequencies below 1 MHz, piezoceramic materials are used to achieve the required sensitivity and recently developments of very small (approx. 1 mm) high quality active elements combined with microcircuit fabrication techniques have enabled new devices to be developed[5]. At medical ultrasound frequencies above 1 MHz, there is less of a need for high sensitivity but a need for very small broadband devices (<1 mm). Here, polyvinylidene difluoride (PVDF) has gained acceptance in metrology as the main piezoelectric material for the active element of miniature hydrophones [6,7]. New developments of piezoelectric materials such as copolymers, thin film piezoceramics and piezoelectric devices mounted on silicon chips offer advantages for specialised applications.

Optical techniques have been widely used for the detection of sound in water. Techniques based on acousto-optic interactions provide reference methods for the characterisation of acoustic fields. Indeed, NPL has established laser interferometry as the primary standard for the calibration of hydrophones in the megahertz frequency range[8]. Alternative interferometric techniques can be applied to the measurement of high-pressure shock waves. For instance, a velocity interferometer is being developed for the reference characterisation of lithotripter fields. A range of other optical techniques offer specific advantages. For instance, single-point optical fibre and focused laser beam sensors offer the advantages of spatial resolution. Techniques involving the optical beam passing through an acoustic beam offer greater sensitivity but often at the expense of integrating the acousto-optic interaction over a line-of-sight or finite volume. Various other optical techniques have been applied and are continually being developed. In certain applications, optical techniques offer advantages over piezoceramic devices.

1.2 METHODOLOGY OF THE STUDY

The two main methods of reviewing the available technologies and assessing their likely impact were a literature review and structured interviews with key users and developers.

1.2.1 Literature review

The literature review consisted of a search conducted using the "INSPEC" search tool, for the period 1985 to 1995. This was refined several times to give a list of approximately 60 abstracts of which approximately 45 papers were deemed to be relevant to this investigation. Current indices, including resources on the world wide web, were also searched to locate additional relevant papers published to date. Further, all these papers were read and used to track-back, using listed references, to investigate research prior to 1985, and to locate other relevant publications not revealed by the literature search. In all more than 100 papers were identified and filtered.

These numerous papers were used to identify two important components for our investigation. The first area identified was the field of study, i.e. a list of the transducer technologies likely to be of greatest interest. The fields of study condensed from the literature obtained were the following:

- condenser microphones
- optical techniques
- piezoelectric materials
- micromachined semiconductor acoustic sensors
- magnetostrictive materials
- force feedback microphones

The second component gained from the literature search was a list of experts and researchers worldwide, identified for being potentially useful contacts for the interview phase of the investigation.

1.2.2 Interviews

A list for telephone interview of those researchers active in the field internationally was compiled by using existing contacts extended with those identified from the literature review. Those on this list were either manufacturers, developers or users.

A questionnaire was devised to act as a standard guide to the interviewer to obtain clear information about the specific interests of the interviewee, and additionally to allow them to expand on key issues and to elicit informed opinion. Topics covered included:

The present position

- types of transducer used,
- the applications they service,
- the length of time since the last significant change in the design of the transducers used,
- a view of the overall technical performance of the transducers used.

A view of the future

- improvements in transducers expected in the future,
- when such improvements would be available,
- what advantages these would bring to the respondents work,
- views on other possible transducer technologies,
- the impact that adopting new transducer technologies could have on the need for traceable calibrations.

The telephone interviews lasted in practice between 15 minutes and 1 hour. To finalise the questionnaire and decide upon which laboratories might be most fruitfully visited a series of 20 pilot interviews preceded the principal body of 28. Additionally 6 visits were made, 3 within the UK and one each in Sweden, Germany and Denmark. The visits enabled a broader appraisal of pioneering work being conducted in key laboratories in the area of transducer technology. 78 people were identified as potential interviewees and altogether 54 provided useful responses in the separate surveys. The geographic scope of this study is shown in Table 1, while Figures 1 and 2 show the distribution of background and main areas of interest among the respondents.

Region	Pilot study	Full study	Visit
UK	12	19	3
Europe (ex UK)	5	7	3
outside Europe	3	2	0

Table 1 Distribution of respondents between geographic region and type of interview.

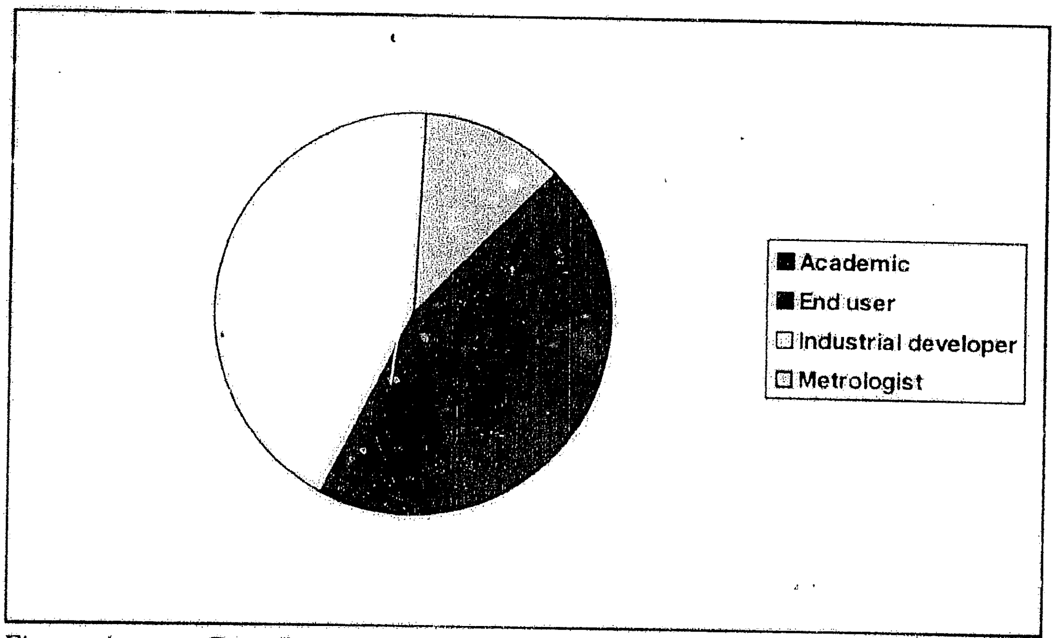

Figure 1 Distribution of backgrounds among the respondents.

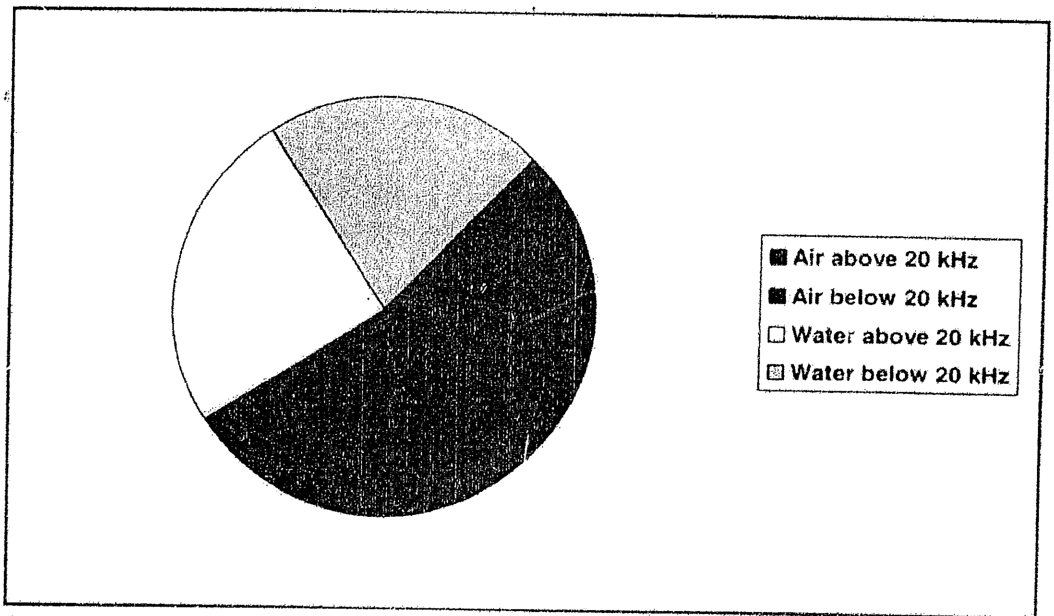

Figure 2 Distribution of main areas of interest among the respondents.

1.3 STRUCTURE OF THIS REPORT

Section 2 of this report reviews the technologies identified in the project, explores their benefits compared with existing options and estimates the timescale in which they can be expected to mature to the point of being useful in the metrology context. It also identifies the UK access route for the technology.

Section 3 highlights some user requirements identified in the survey and uses these to identify which technologies are likely to have the highest impact on acoustic metrology in the next ten years.

Section 4 makes recommendations on the strategy that should be adopted by the UK National Measurement System with respect to each of the high impact technologies.

The study has concentrated on preparing a strategy for the *new* developments in acoustic transducer technology at the expense of a detailed analysis of the incremental improvements in existing technologies. This was intentional. It is easy to be blinkered and assume that all developments will start from current best practice. Occasionally new developments are radical and come from unexpected sources, so the search was wide and preferred those technologies which were not currently exploited at NPL.

Some technologies were rejected because their application to metrology in the next decade seemed unlikely. For example, the interaction between ultrasound and sound can be used for both a detector[9] and a source[10] but the physical understanding of the processes involved requires some development before any metrological application could become clear.

2 TRANSDUCER TECHNOLOGIES

In any area of metrology the aim is to measure some quantity without that measurement disturbing the system that is to be characterised. In acoustics, particularly in air, this is difficult.

The introduction of a sensor into an acoustic field will change the field as it diffracts around the sensor. To minimise this, the sensor must be much smaller than the wavelength of the sound. The wavelength of sound in air at 10 kHz is about 30 mm so an ideal transducer would be no larger than 0.3 mm. Typical measurement microphones are about 15 mm. The wavelength of sound in water at 10 kHz is about 150 mm and at 10 MHz is about 0.15 mm. Current hydrophones are of similar size.

The introduction of a sensor into a field will also change the field due to reflection if there is a mismatch between the characteristic acoustic impedance of the sensor and that of the propagating medium. This is particularly important for optical measurement techniques. In water it is possible to introduce a thin film (called a pellicle) where its displacement in the acoustic field follows that of the propagating medium and therefore does not disturb the field. Then the motion of the pellicle can be determined interferometrically and thereby characterise the field. The specific acoustic impedance of air is some 3500 times less than that of water and no equivalent of the pellicle has been found. Smoke particles are suitable at a few hundred hertz[11] but fail at higher frequencies.

The effects of diffraction and reflection have to be quantified as part of the calibration of the transducers and so most acoustical transducers are calibrated only for use in specific types of field.

Transducers for airborne sound at audio frequencies are primarily concerned with characterising sound fields to assess the annoyance or health risks to humans.

Transducer materials for ultrasonics frequencies have applications primarily in liquids and solids. Three main areas are Marine Acoustics (sonar), Medical Ultrasound (diagnostic imaging and therapy) and Industrial Ultrasound (nondestructive testing (NDT); gas ignition; welding; cleaning; gas and liquid flow sensing; distance and vibration measurement; sonochemistry; actuators and consumer audio). To be useful, transducer materials have to be readily available, possess reproducible properties, be capable of formation into transducers at reasonable cost and meet stringent performance requirements. More recently, the application of optical techniques has led to new forms of transducer.

Progress in transducer technologies is motivated by many factors in what is a complex, fragmented and highly competitive market. Higher resolution is sought in medical imaging to improve diagnostic capabilities. The defence industry is interested in greater sensitivity, generating higher acoustic powers and in developing large scale arrays for better directional information. Industrial processes involving sonochemistry also demand higher powers to increase throughput and efficiency. For hostile environments non-contact optical techniques such as optical fibres may offer advantages. Recent developments in high pressure ultrasonics in the MHz region necessitate small scale but robust hydrophones. Again, optical fibres offer potential of having a high spatial resolution, broad bandwidth and robustness.

The following list of competing acoustic transducer technologies should not be considered exclusive. While making an appraisal of the field to distinguish future trends, the possibility of novel techniques whose development is swift must be allowed for.

2.1 CONDENSER MICROPHONES

Condenser microphones have been used for measurement and realising the primary measurement standard for sound in air for nearly 50 years.

A condenser microphone is a parallel plate capacitor in which one plate is fixed rigidly while the other moves in response to a sound pressure. The capacitor is charged through a very high resistance. The displacement of the movable plate (diaphragm) is proportional to the sound pressure and as the resistance prevents charge leaving the capacitor, the voltage across the capacitor is also proportional to the sound pressure. The microphone is calibrated in terms of voltage per unit sound pressure.

In a typical modern condenser microphone the diaphragm is only a few microns thick and is held, under tension, several tens of microns from a perforated back plate. The diaphragm is so thin and flexible that the dominant force opposing its motion is this tension rather than the stiffness of the diaphragm material. The back plate is perforated because otherwise the trapped air would add considerably to the stiffness of the diaphragm and the motion would be highly damped. The air volume behind the diaphragm is closed except for a small vent which allows the static pressure either side of the diaphragm to equalise so that the microphone does not respond to changes in barometric pressure. A designer will vary the diaphragm spacing, the mass of the diaphragm, and the back plate perforations to produce a microphone with a desired sensitivity and frequency response. The frequency response can even be tailored to compensate for diffraction effects in the sound field around the microphone.

For best sensitivity, the electrode spacing is made as small as possible constrained by the risk that the diaphragm may collapse onto the backplate or that a spark may jump the air gap. The equalising vent controls the very low frequency response and the microphone has a poor sensitivity to sound waves with a period comparable with the pressure equalisation time. Above this point the frequency response can be described by three parameters; a mass, a compliance and a resistance. Below the resonance frequency the response is flat and controlled by the compliance. Increasing the compliance increases the sensitivity (as more energy is coupled into the microphone) but this also decreases the resonance frequency. As the response falls at 12 dB per octave above the resonance frequency, this limits the usefulness of the microphone at higher frequencies. The resonance frequency is inversely proportional to the square root of the mass and the compliance so for the best high frequency response a light diaphragm is required. The shape of the frequency response around resonance is controlled by the resistance.

The mass, compliance and resistance are controlled by the design of the microphone. The compliance is determined by the tension in the diaphragm. This is adjusted during manufacture by stretching the diaphragm over a tensioning ring. The mass is generally controlled by the thickness and material of the diaphragm. In general the diaphragms are chosen to be as thin as possible with regard to the risk of rupture or pin holes. With metal diaphragms there is little to be gained by reducing the thickness below one micron as then the mass of air moved with the diaphragm is generally larger than the diaphragm mass itself. The resistance is determined by the number and size of the holes in the backplate. The disadvantage of using resistance to control the diaphragm at resonance is that it introduces thermal noise into the system and can limit the usefulness of the microphone at low sound pressures.

Condenser microphones are generally well suited to the measurement applications for which they are used. Most respondents to our interviews expressed satisfaction with their sensitivity, frequency response and dynamic range. Improvements requested centred on cost, long term stability and temperature stability.

The technology used in the design and manufacture of condenser microphones is mature. Although the principles have been well understood for several decades, new materials and construction techniques have been employed. For example, the use of electret materials to provide the polarising voltage or diaphragm materials that are more resistant to corrosion. Advances may come in the future from transducers which effectively change the active size of their diaphragms with frequency to give better directional characteristics. But currently the manufacture of condenser microphones still relies on craftsmanship. It is reminiscent of a jeweller at work rather than modern manufacturing technology. Future advances are most likely to be aimed at ease of production and improvements in their long term stability.

2.1.1 UK access route

At present there is no UK manufacturer of condenser microphones and UK manufacturers of acoustical instruments source their microphones mainly in Europe.

2.1.2 Relevant papers

Frederiksen E, 1996.
Reduction of non-linear distortion in condenser microphones by using negative load capacitance.
Proc Internoise 96, 2679 - 2684.

Ginn B, Frederiksen E, Gramtorp J, Larsen H, 1994.
Microphones, preamplifiers and calibration: new products and new possibilities.
Internoise 94, 1959-1962

Jarvis D R, 1995
Measurement standards for acoustics
Proc IOA **17**, Part 5, 47-52

Power J, 1996.
Controlling the directional characteristics of acoustic transducers.
UATG meeting on New Transducer Technologies, August 1996.

Rasmussen G, 1996.
Progress in acoustic transducer design.
Proc IOA, **18**, Part 1, 13-19

2.2 CAPACITIVE TRANSDUCERS FOR ULTRASOUND

Capacitive transducers for ultrasound are used primarily in air though it is possible to use them underwater if they are waterproofed. They are particularly suitable for air because their characteristic acoustic impedance more closely matches that of the air than with other types of ultrasonic transducer.

The most ... nmon form of this transducer is the range finder found on Polaroid cameras. In other applications these transducers are often constructed in phased arrays that allow two and three-dimensional ranging for robotics.

Condenser microphones are limited in their high frequency response by the mass of the diaphragm. Microphones designed to work at higher frequencies have smaller diaphragms to reduce their mass but this also reduces their sensitivity. Capacitive transducers for ultrasound overcome this problem by behaving like multiple miniature condenser microphones in parallel.

The principle under which these transducers operate is identical to the condenser microphone except that the diaphragm has an insulator applied to its underside and is brought into contact with the backplate. Air becomes trapped between the backplate and diaphragm in pockets formed by the roughness of the two materials or sometimes in features machined into the backplate. Each trapped air pocket forms a miniature condenser microphone, and because each miniature diaphragm is small it has a high frequency response and because there are many in parallel the sensitivity can be useful. The frequency response of such a device is not as simple as for a single condenser microphone. Each individual element will have a resonance governed by the same considerations as the condenser microphone but the response of the whole device will be governed by the summation across many varied elements. Much of the recent research into these devices has concentrated on the design of backplates in order to achieve control of the frequency response. Various technologies have been tried including silk-screening, milling, laser etching and micromachined silicon with a silica insulator.

The frequency response of these devices has been widening rapidly over recent years. The Polaroid device worked at 50 kHz with a bandwidth of 20 kHz. More modern transducers work from below 100 kHz to over 2 MHz. It is not clear if the lower frequency limit is inherent to the transducer or introduced as a high pass filter in the electrical circuits. The transducers are often connected to charge amplifiers containing high pass filters rather than audio frequency preamplifiers but if the voltage from the transducer is monitored on an oscilloscope then it is clear that the transducer does respond at audio frequencies.

Some problems remain with these transducers. None, apart from the Polaroid one, are being produced commercially, they remain in the research laboratories. Problems arise with some insulators on the diaphragms, which can take up a charge that counteracts the polarising voltage. There is no information on the stability of these devices in the long term. Indeed the research into these devices is not aimed at producing an equivalent of the measurement microphone, and many of the applications that they are aimed at do not require the devices to be stable or have a wide frequency range or wide dynamic range. Many researchers report that they are unable to calibrate these devices because no measurement standards exist above 40 kHz. Similarly it is not possible to measure exposure to airborne ultrasound because none of these transducers have been calibrated. It is possible that some of these transducers could be calibrated by the free-field reciprocity method and this could be the starting point for the development of a primary standard. No doubt the transducers will need considerable development before they become as good as measurement microphones.

2.2.1 UK access route

Development of these transducers for non-destructive testing and as ranging transducers is taking place at Warwick and Nottingham Universities. There is no activity concerned with developing these transducers for metrological use.

2.2.2 Relevant papers

Anderson M J, Hill J A, Fortunko C M, Dogan N S, Moore R D, 1995.
Broadband electrostatic transducers: modelling and experiments.
J Acoust Soc Am **97**, 262-272

Bergqvist J, Gobet J, 1994.
Capacitive Microphone with a Surface Micromachined Backplate Using Electroplating Technology.
J Microelectmech Systems, **3**, 69-75

Carr H, Munro W S H, Rafiq M, Wykes C, 1992.
Developments in capacitive transducers.
Nondestr. Test. Eval., **10**, 3-13

Carr H, Wykes C, 1993.
Diagnostic measurements in capacitive transducers.
Ultrasonics **31**, 13-19

Mattila P, Hietanen J, 1994.
Bandwidth control of an electrostatic ultrasonic transducer.
Sensors and Actuators A **45**, 203-208

Munro W S H, Wykes C, 1994.
Arrays for airborne 100 kHz ultrasound.
Ultrasonics **32**, 57-63

Rafiq M, Wykes C, 1991.
The performance of capacitive ultrasonic transducers using v-grooved back plates.
Meas. Sci. Technol **2**, 168-174

Schindel D W, Hutchins D A, Zou L, Sayer M, 1995.
The design and characterization of micromachined air-coupled capacitance transducers.
IEEE trans. ultrasonics, ferroelectrics. **42**, 42-50

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Schindel D W, Hutchins D A, Zou L, Sayer M,
1992.
Capacitance Devices for the Generation of Air-Borne Ultrasonic Fields.
1992 Ultrasonics Symposium, 843-846

2.3 MICROMACHINED ACOUSTIC SENSORS

Micromachining is a rapidly growing field in which sensors and actuators are fabricated using technology similar to that applied to integrated circuit manufacture. Mechanical structures, such as cantilevers and diaphragms, can be formed in silicon or diamond. Two distinct technologies can be used; bulk micromachining involves the etching of mechanical structures from bulk wafer silicon while in surface micromachining the mechanical structures are obtained by the patterning of thin layers of material. Micromachining in silicon can produce miniature structures with high precision, high repeatability and high integrity. It offers low unit cost when large batches are involved and has the potential of integrating electronic components with mechanical structures on the same chip.

3D structures can be fabricated on a single crystal of silicon by anisotropic etching. Chemicals such as potassium hydroxide, hydrazine, and ethylene diamine have different etch rates along different crystal planes giving a characteristic angle of 57.5° in many structures. The etching process can be stopped at places on the surface by a resistant coating and at a point in the crystal by ion implantation. Structures as small as 4 µm can be reliably produced. Other materials can be combined with the silicon to give different properties. Boron ions can be implanted to change the crystal structure, layers of silicon oxide or silicon nitride can be formed and diamond films can be deposited.

Micromachined sensors include microphones, pressure sensors and accelerometers. Bulk silicon micromachining also finds applications in chemical sensors, pumps, valves, magnetic or thermal actuators and resonators.

Micromachined microphones will find particular applications in arrays where they can be used for noise cancelation and source location. Possible applications include:

- hearing aids where the signals from an array of microphones[12], say on the arm of a pair of spectacles, could be processed so that the hearing aid amplified sounds coming from the direction in which the user was looking and rejected sounds from other directions.

- car phones and conference facilities[13] where the signals can be processed to select a specific speaker in preference to other sounds.

- gun shot locator. One American respondent in the survey reported that a system of microphone arrays on lampposts had been suggested for identifying the sources of gun shots in urban areas!

The development of these array techniques can require the phase response of the individual elements to be calibrated and compensated for by signal processing.

Most work on micromachined silicon sensors has concentrated on sound in air but there are examples of fluid filled transducers being used as hydrophones.

2.3.1 Design of micromachined diaphragms

Many of the processes associated with producing micromachined diaphragms are determined by ease of production, unit cost and yield. These are not the prime concern of this study. Instead, the factors which influence the electroacoustical properties of the transducer will be highlighted.

Methods of sensing the motion of the diaphragm will be covered in the next section but whichever sensing method is chosen, the mechanical response of the diaphragm to the sound wave dominates the properties of the transducer. This mechanical response follows the same principles as those outlined for the condenser microphone and can, in its simplest form, again be analysed in terms of a mass, compliance and resistance.

The compliance of the diaphragm is not controlled by placing it under tension but by changing the inherent stress in the material during the production processes. For example boron doping of silicon changes the crystal structure and reduces the stress. Laying down silicon nitride at high temperature and allowing it to cool results in a high tensile stress, but laying down silicon oxide in a similar manner results in a compressive stress. A mixture of these two layers can result in some control over the compliance of the diaphragm. Chemical control can result in poor repeatability between batches and an alternative, more repeatable method, is to control the compliance by machining corrugations into the diaphragm.

The mass of the diaphragm is controlled by its area and thickness. Typical thicknesses are 0.2 μm with an area of 1 mm^2 giving a mass of 7×10^{-10} kg or 4000 times smaller than the mass of the diaphragm of a typical half-inch condenser microphone. Consequently the diaphragms can be useful at much higher frequencies. A recent paper by Thielemann demonstrates a silicon microphone with a flat frequency response to above 180 kHz and models microphones that could work to beyond 1 MHz with a sensitivity of 1.8 mV/Pa.

The resistance of the diaphragm is controlled by the design of the backplate and has the same effect as in a condenser microphone.

Silicon microphones should be inherently more stable than condenser microphones. The various materials used in their manufacture are more similar in their thermal coefficients so thermal shocks should not be a problem. The diaphragms are not under mechanically restrained tension so there is less likelihood of a mechanical shock causing change in sensitivity. The long term stability may be influenced by changes in the crystal structure. For example boron doping reduces the tension in the diaphragm by breaking the crystal structure, if the crystal were to re-grow over years then the tension in the diaphragm would slowly increase.

2.3.2 Sensing methods for micromachined diaphragms

Several methods of sensing the motion of the diaphragm have been tried in the past decade:

Capacitive
Miniature microphones working on the capacitive principle work in the same way as condenser microphones. They mostly use external polarisation voltages but electret materials have been used instead, though this may affect the stability. At present this technology appears to give the best sensitivity and dynamic range.

FET
In an FET (field effect transistor) microphone the membrane vibrations modulate the gate-channel capacitance and thus the drain current. Although work on this technology continues, it is at present limited by the 1/f noise in the FET.

Piezoelectric
The piezoelectric effect can be used to sense the motion of a silicon diaphragm by applying a layer of material such as PVDF. It is then necessary to add electrodes to the diaphragm surface. A complicated electrode structure is needed since the strain of the piezoelectric layer is of the opposite sign in the central region and at the periphery of the membrane. A series connection of the inner and outer electrode sections ensures that the piezoelectric signals of both regions are added in phase.

Piezoresistive
A piezoresistive sensing arrangement consists of four polysilicon resistors positioned on the membrane. Two resistors are placed in the centre region and two in the border region. All four are combined in a Wheatstone bridge in such a way that the opposite piezoresistive effects generated by the inner and outer resistors due to the opposite strains are added in phase. A microphone of this type is being used as a feedback microphone in a commercial sound calibrator. In this unique environment the microphone only has to meet a specification at a single frequency and in a limited dynamic range and its major advantage is the ease with which its output signal can be integrated into the control circuit of the calibrator.

Optical-waveguide
The optical waveguide sensing method depends on the fact that the amplitude and phase of a light wave propagating in an optical wave guide depends on the waveguide dimensions or on changes in the vicinity of the waveguide. A microphone using this effect thus converts an acoustic signal into an intensity or phase modulation of a light wave. At present these devices have higher self induced noise than other types of microphones but they have definite advantages if microphones needed to be integrated with optical communication systems or used in hazardous environments.

The key quantities from any sensing method are the sensitivity (does it produce a useful output that can be processed easily?), the equivalent noise level (what is the lowest acoustical input that can be distinguished from the self generated noise of the microphone?) and the capacitance or impedance of the device (how good must the pre-amplifier be?). Table 2 summarises these quantities for each sensing method.

Sensing method	Sensitivity Pa^{-1}	Equivalent noise level dB (A)	Capacitance or Impedance
capacitive	3 mV	30	4 pF
FET	10 mV	62	1 kΩ
piezoelectric	0.12 mV	55	15 pF
piezoresistive	0.5 mV	44	5 kΩ
optic-waveguide	0.05 rad	45	-

Table 2 Comparison of silicon microphone sensing technologies

2.3.3 Micromachined transducers for ultrasound in air at MHz frequencies

As reported above silicon microphones could be designed with useful frequency responses up to 1 MHz. A micromachined transducer has recently been described which will extend this frequency range to 10 MHz and beyond[14]. The principle is similar to the extension of condenser microphone technology to the capacitive transducers for airborne ultrasound. The sensor is constructed to have many independent sensing elements in parallel, instead of diaphragms supported at their edge. These are more like mushrooms, diaphragms supported by central stalks. The motion of the elements is again detected by a change in capacitance.

The metrological applications of these devices are unlikely to appear in the next ten years.

2.3.4 UK access route

There are UK manufacturers and research organisations actively pursuing the development of silicon microphones for commercial applications but the main academic interest is at the Technical University of Darmstadt in Germany.

2.3.5 Relevant papers

Capacitive

Bergqvist J, Rudolf F, 1994.
A silicon condenser microphone using bond and etch-back technology.
Sensors and Actuators, A, 45, 115-124

Bernstein J, 1992.
A Micromachined Condenser Hydrophone.
Tech Digest, IEEE, South Carolina, USA, 161-165

Bruneau M, Bruneau A M, Dupire P, 1995.
A model for rectangular miniaturized microphones.
acta acustica 3, 275-282

Kuhnel W, Hess G, 1992.
Micromachined subminiature condenser microphones in silicon.
Sensors and Actuators, A, **32**, 560-564

Rudolf F, Bergqvist J, 1991.
Silicon Micromachining for Sensor Applications.
Microelectronic Eng **15**, 399-406

Scheeper P R, Olthuis W, Bergveld P, 1994.
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J Micromech, Microeng **5** 106-108

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Proc. IOA **18**, Part 1, 29-32

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Sensors and Actuators A **46-47**, 151-155

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Sensors and Actuators A, **37-38**, 484-488

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Sensors and Actuators 7, 347-360

Schneider U, Schellin R, 1994.
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Sensors and Actuators A, **41-42**, 695-698

2.4 PIEZOELECTRIC TRANSDUCERS

The term piezoelectric describes the ability of a solid to generate a voltage when subjected to a mechanical stress, or the ability to generate a mechanical force when subjected to a voltage. This interaction between electric charge and mechanical deformation has been used for the production and sensing of sound since the late 19th century. Quartz and other natural materials were replaced by ceramic materials such as lead zirconate titanate (PZT) in the late 1950's, and plastic materials such as polyvinylidene difluoride (PVDF) developed in the 1970's. Application of these materials has principally been to underwater acoustics, airborne application generally being limited to sounders (e.g. fire alarms), range finders and flow meters.

Application in air is limited by the large impedance mismatch between piezoelectric materials and air. This can be mitigated by the use of aero gels and other structures[15] which provide a matching layer. However, these are generally tuned to a specific frequency and are not suitable for the broad bandwidth transducers required for metrology.

Piezoelectric transducers are particularly suited to driving mechanical structures which in turn can affect how sound is propagated into air. In this way they can be used for active control of noise[16].

Piezoelectric hydrophones are widely used in medical ultrasound applications and are often of a membrane design; sections of un-poled polymer film with small piezoelectrically active regions convert the incident acoustic pressure waveform into an electrical signal. Alternatively they can comprise a single small (~ 0.5 mm diameter) element in a needle probe arrangement. A sensing element should be smaller than, or comparable with, the acoustic wavelength to avoid diffraction effects. For propagation in water this varies from 1.5 to 0.1 mm for the frequency range 1 to 15 MHz. The lower limit on the dimension of the element is determined by the sensitivity of the piezoelectric material.

2.4.1 Piezoelectric polymer materials

Since 1980 polyvinylidene difluoride (PVDF), which is a piezoelectric polymer, has formed the standard membrane hydrophone for use in medical ultrasound[6,17].

Advantages of piezoelectric polymer materials are:

- Hydrophone designs are relatively well established and understood.
- High hydrostatic piezoelectric coefficient.

- Low acoustic impedance, close to that of water.

- Broad bandwidth. This enables accurate measurement of short acoustic pulses, especially useful for pulse-echo work. The frequency response is flat if the thickness resonance mode is above the working frequency.

- PVDF offers great design flexibility by being producible in various forms: powder; pellets; foil; tube. It can also be used in sheet form as a large aperture sensor or can be formed into a cable. This can constitute either a distributed sensor or be wound into a planar spiral to form a large area transducer (20 cm diameter or more). A constraint on the shape is that the PVDF must be in a stretched (polar β) form. It is mechanically robust and light weight.

- There is potential with this material to form "smart" materials which may operate anechoically by reflecting a pressure waveform in antiphase.

Disadvantages of piezoelectric polymer materials are:

- PVDF is not a good transmitter and is normally used to receive, whereas PZT ceramic is useful as both transmitter and receiver. Its application in projectors is limited to low power high frequency devices.

- In common with other transducers where electronics are present at the sensing end, the method is susceptible to electromagnetic interference.

- Electrical contacts are achieved using thin film coating techniques. Variation in surface quality of the manufactured film can lead to poor quality coatings; this is especially problematic when producing small active elements.

Copolymer materials of Vinylidene Fluoride and Trifluoroethylene (VDF and TRFE) can show higher piezoelectric responses than PVDF and are not restricted to stretched shapes. During processing these materials crystallise into the appropriate form without need for mechanical orientation, which enables versatile forms such as spheres to be produced using conventional injection or compression moulding.

2.4.2 Piezoelectric ceramic materials

PZT, lithium niobate, barium titanate and lead titanate are examples of ceramic materials which exhibit piezoelectric properties. These materials are powerful transmitters and are widely used in underwater acoustics, medical ultrasound and NDT transducers.

Advantages of piezoelectric ceramic materials are:

- PZT, for example, is well established as both a powerful projector and as a receiver of acoustic waves. This class of material forms the mainstay of marine acoustic transducer manufacturing as well as for NDT.

Disadvantages of piezoelectric ceramic materials are:

- There are several resonance modes present in ceramics and so the frequency response is not smooth.

- Usually only simple forms, such as discs, blocks, tubes and spheres, can be produced.

- The materials are relatively brittle and susceptible to mechanical shock damage.

- The method is susceptible to electromagnetic interference due to the presence of electronics at the sensing end.

2.4.3 Composite piezoelectric materials

Composites attempt to combine the properties of two or more materials so that advantages can be pooled. For example a combination of high electromechanical coupling, absence of radial modes (internal damping) and good matching to water is desirable. PZT is a good transmitter whereas PVDF is a good receiver so a transducer made from both materials may have both properties. PZT is not acoustically well matched to water, so in a method known as "Dice and Fill" a cube of PZT is located in a PVDF surround that is better matched to the surrounding water. Similarly, the hydrostatic coefficient (therefore the sensitivity) can be enhanced using composites. As an alternative to PVDF an inert polymer can be combined with PZT to reduce planar stresses within the ceramic.

Advantages of composite piezoelectric materials are:

- They can be fabricated in varied forms, using injection moulding for example. It is possible to produce transducer profiles which are shaped to focus the beam.

- They can be fabricated so that they operate more like a piston source, with a better beam and frequency response. This is achieved by the damping out of radial modes in composites, however some efficiency is inevitably lost by this process.

Disadvantages of composite piezoelectric materials are:

- Composite materials can be complex and therefore expensive to manufacture, but the technology is developing rapidly.

- The method is susceptible to electromagnetic interference due to the presence of electronics at the sensing end.

2.4.4 UK access route

Within the UK there are many manufacturers of acoustic systems which utilise piezoelectric materials, particularly in the defence industry. DRA (Winfrith) and Ferranti-Thomson (Fleet) are manufacturers of sonar systems, and GEC-Marconi (Caswell, Templecombe) also develop naval systems. Morgan-Matroc is a major manufacturer of piezoceramic materials. There are additionally several small companies such as Precision Acoustics (Dorset) and Marine Acoustics which produce hydrophones for specific markets.

2.4.5 Relevant papers

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Proc Oceans Eng Sept 1994, Brest, France I-358-363

Sherman C H, Butler J L, 1995.
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Volume-Sensitive Piezoelectric Composites for Electroacoustic Transducers.
Ferroelectrics, **143**, 287-298

Ting R Y, 1994.
Composite Piezoelectric Materials for Transduction.
Applied Acoustics **41**, 325-335

2.5 MAGNETOSTRICTIVE MATERIALS

This principle is based upon the change in shape which can be experienced by certain materials, termed magnetostrictive, when subjected to an external magnetic field. A rod of magnetostrictive material which is wrapped in a coil will change its longitudinal dimension when alternating current is passed through the coil; the device transduces the alternating current into vibration energy of the same frequency. The technology has a long history but is receiving increasing interest through the development recently of TERFENOL-D which is termed "giant-magnetostrictive" because of its ability to achieve strains 40 times that of conventional materials in this class. It was developed as a high power underwater projector for sonar but is now finding broader application including airborne (i.e. loudspeakers).

Advantages of magnetostrictive materials are:

- their ability to be energised remotely by a magnetic field, with no need for direct electrical contact. This facility may be particularly attractive for medical applications.
- They can deliver high powers and large movements. They are expected to rival PZT in welding and cleaning applications in the future.
- They are durable and can be applied in harsh environments.
- They are flexible in form; for example, metallic glass magnetostrictive materials in the form of thin ribbons can be configured in various ways to make hydrophones.

Disadvantages of magnetostrictive materials are:

- their low frequency range of up to around 80 kHz. This is due to eddy current losses. In the future this range may be extended by using composites or lamination techniques.
- Magnetostrictive transducers are relatively bulky, of high cost and more complex in design than other transducers.
- The method is susceptible to electromagnetic interference due to the presence of electronics at the sensing end.

Particular applications include actuators, fluid injection, "thumpers" for seismographic use and anti-resonant optical tables for stability and anti-resonant panels in cars to reduce noise. If the frequency range can be extended there could possibly be application to lithotripsy. Until the technology is developed further, its interest will be limited to certain low frequency applications where high movement or acoustic power is a priority.

2.5.1 UK access route

There are currently no major manufacturers of magnetostrictive materials in the UK but several companies are developing applications for the materials. Hull University has a small research group in this area (Dr R. Greenough) while the major manufacturers are Edge Technologies in the USA and Feredyn in Sweden.

2.5.2 Relevant papers

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J Acoust. Soc Am 94, 636-641

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InTech, March 1987, 51-55

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Metallic Glasses as Acoustic Transducers.
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Greenough R D, 1996
High power magnetostrictive actuation
UATG meeting on new transducer technology, Nottingham.

2.6 OPTICAL TECHNIQUES AND TRANSDUCERS

Optical sensing of acoustical fields involves a monochromatic beam of light being modulated in intensity, polarisation or phase in proportion to the acoustical pressure. The light may be guided within an optical fibre. These are intrinsically sensitive to many stimuli (such as temperature, pressure, strain), affecting the light which passes through them. Alternatively such fibres are useful for guiding light to an extrinsic sensitive element, such as a polymer membrane, and coupling the light back to a detector for measurement of the modulated parameter. Both intrinsic and extrinsic fibre sensors have been fruitfully researched in recent years. Further optical techniques applied to acoustic sensing include both Michelson and Fabry-Perot interferometers to form microphones, as well as ultrasound sensors. Optical fibre microphones are under development at several establishments and optical techniques are finding application in both airborne and waterborne acoustics.

The relatively recent availability of low cost, reliable optical components has enabled the application of optical sensors to the field of acoustics, and this area of research is expanding rapidly. The following points outline attractions and considerations relating to this technology:

Advantages of optical techniques are:

- Optical measurements can be absolute, and are referenced to the wavelength of light.

- Optical techniques have the advantage that the critical sensing element can be light weight and small scale, of the order of tens of microns. This property offers high spatial resolution. Further, the dimension can be small with no, or negligible, loss in sensitivity; for magnetostrictive or piezoelectric materials the sensitivity depends on the material dimension. The small size of optical fibre components harmonises with the need for large scale arrays of sensors with a high packing density to record the spatial distribution of fields. Fibre-based components are easy to guide and can be sterilised for insertion *in vivo* using a stent or catheter. Additionally, small size imparts an omnidirectional sensitivity, and optical techniques can be virtually, or entirely, non-perturbing to the ultrasound field being measured.

- A high bandwidth is offered, in water it can effectively be limited by that of the supporting electronics (typically 100 MHz).

- In laser generation of ultrasound the source is located at the surface of the material under inspection and so follows the surface contour precisely. A laser induced ultrasound pulse resembles a delta function, the optimum for NDT, without the ringing that can result with a piezoelectric ceramic.

- Non-contact or remote methods for both generation and detection of ultrasound are feasible using optical beams and this has the advantage that acoustic coupling is not necessary. Measurements can be made in hostile environments where direct access to a surface under test in NDT, for example, may be denied. Remote sensing means that high acoustic pressures (over 100 MPa) can be measured without instrument damage. Conventional accelerometers are disadvantaged by their integral mass; non-contact methods are favoured here.

- Immunity to electromagnetic radiation and crosstalk are key advantages of optical techniques.

- Optical technologies are well established and reliable components, widely used in the telecommunications and other industries, are readily available; these are compatible with communications technology. Optical fibres can multiplex a group of signals from discrete fibre sensors.

- Lack of electronics at the sensing end is attractive for medical applications or where the environment is hostile, such as in the ocean.

- Optical techniques can facilitate otherwise complex configurations, such as scanning a fibre across a transducer face.

Disadvantages of optical techniques are:

- The costs for implementing an optical system are higher than one utilising conventional transducer materials. However, some types of optical probe can be made cheaply and can be effectively disposable.

- In general optical techniques have low sensitivity in comparison with piezoelectric materials, which offer a better signal-to-noise ratio.

- That optical fibres are sensitive to several stimuli gives potential for cross-sensitivity. This must be carefully considered during the design stage. This is particularly the case where an optical fibre is wound on a mandrel.

Although only a relatively small number of our interviewees were actively researching optical technologies, virtually all identified this as an area set for expansion over the next ten years.

Fibre hydrophones have been used in towed arrays and installed under the ice in the Arctic. An optical biopsy system capable of real-time *in vivo* diagnosis of tissue pathologies has been developed, where absorption spectroscopies are obtained using optical fibre probes. Optical generation of ultrasound using high-power lasers has been applied to medical physics, for example in laser-guided angioplasty, and in industry for materials inspection. Laser generated ultrasound is useful for yielding information from beneath a surface whereas an optical beam will respond to the surface itself. Optical fibre sensors are under investigation to detect *in vivo* the acoustic pressures associated with lithotripsy treatment. Demands on calibration techniques for fibres are that there needs to be good repeatability, especially when arrays contain a high density of elements, and also directional information will be important. Optical systems based around *in vivo* probes are expected to be commercially available within 10 years, and available for research within 5 years. From the results of our survey it is considered unlikely that a major demand for the calibration of optical instruments for acoustics will arise within 10 years, however a demand for calibration of acoustic fields by optical methods exists now.

Worth mentioning is a sophisticated technique known as Optical Diffraction Tomography (ODT). This is an optical technique for the measurement of ultrasound in air or water. Raman-Nath diffraction in conjunction with topographic algorithms form the basis of this technique which has been used for measurements on ultrasound from 0.5 MHz - 10 MHz in water and 0.2 MHz to 1 MHz in air. Continuous wave (CW) and tone-burst excitation as well as plane and focussed ultrasound have been studied. The spatial resolution is comparable with 0.5 mm hydrophones and the bandwidth is 10 MHz. High-intensity ultrasound measurements (e.g. on lithotripters) have not been realisable as theoretical approximations in the Raman-Nath theory do not apply for high pressures in focussed fields. The pressure and phase in cross-section can be determined at any distance from the transducer face. Both the Physikalisch-Technische Bundesanstalt in Germany and the University of Lund in Sweden have considerable expertise in this area. ODT has advantages over hydrophone technology in that this is an absolute method for determining acoustic pressure; it is non-perturbing in that no probe need be inserted into the ultrasound field; it has potentially better spatial resolution than current hydrophones; the method can be applied to airborne ultrasound.

2.6.1 UK access route

In the UK the centres for this technology are at the University of Kent at Canterbury (for sensing of pressure, temperature, vibration and bio-sensors), University College London (optical bio-sensors), AWE at Aldermaston (optical sensing of shockwaves), and DRA at Winfrith (optical hydrophones).

2.6.2 Relevant papers

Fibres

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Proc of SPIE, **412**, April, Arlington, 136-141

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J Acoust Soc Am **98**, 1612-1617

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J Acoust Soc Am **98**, 1618-1622

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Sov Phys Acoust **35**, 632-635

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Meas Sci Technol **7**, 908-910

Nakamura K, Uno Y, Iga K, 1996.
Sound field measurements by a sharply bent optical fiber.
J Acoust Soc Jpn (E) **17**, 45-47

Patrtnottre A, et al, 1993.
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Sensors and Actuators A, **37-38**, 489-493

Rao Y, Jackson D A, 1996.
Recent progress in fibre optic low-coherence interferometry.
Meas Sci Technol **7**, 981-999

Suhadolnik A, Babnik A, Mozina J, 1995.
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Proc of SPIE **2510**, 120-127

Wu Y Q, Shankar P M, Lewin P A, 1994.
Characterization of ultrasonic transducers using a fiberoptic sensor.
Ultrasound in Med & Bio, **20**, 645-653

Zhou C, Letcher S V, Shukla A, 1995.
Fibre-optic microphone based on a combination of Fabry-Perot interferometry and intensity modulation.
J Acoust Soc Am **98**, 1042-1046

Interferometry

Beard P C, Mills T N, 1996.
Extrinsic optical-fiber ultrasound sensor using a thin polymer film as a low-finesse Fabry-Perot interferometer.
Applied Optics, **35**, 663-675

Chu J H, Bak Y H, Kang B K, Kim U, 1992.
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Optics Comm **89**, 135-139

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Optical method for determining the frequency response of pressure-measurement systems in respiratory mechanics.
Med & Bio Eng & Comp. Jan 1986, 78-82

Kersey A D, 1990.
Recent progress in interferometric fiber sensor technology.
Proc of SPIE **1367**, Fibre optic and laser sensors VIII

Matsuda Y, Nakano H, Muto K, Nagai S, 1992.
Calibration of acoustic emission sensors with laser-generated ultrasonic wave.
J Acoust Soc Jpn (E) **13**, 91-96

2.7 FORCE FEEDBACK MICROPHONES

Force feedback is a method of improving the linearity and dynamic range of an acoustic transducer. A microphone with negative force feedback applied around it has an output that is a measure of the force required to hold the diaphragm still, rather than having an output proportional to the displacement of the diaphragm. The feedback reduces the displacement of the diaphragm by a factor of one plus the loop gain. (The diaphragm would only actually be held still if the loop gain were infinite.) The maximum pressure to which the microphone can accurately respond is likely to be determined by the maximum amount of force available from the feedback rather than the range of the measuring system. The feedback also reduces the distortion, again by a factor of one plus the loop gain, thus improving the linearity. The feedback itself has no effect on the self noise of a given transducer but with feedback controlling the response at resonance it is no longer necessary to have a large acoustical resistance in the diaphragm and so the thermal noise in the diaphragm can be minimised.

The most important result of the negative feedback is that the frequency response of the microphone is no longer dictated by the behaviour of the diaphragm, but is instead controlled by the electronics in the feedback path.

In prototype studio microphones the force feedback is applied by two electrodes, one either side of the diaphragm. This arrangement allows for a linear relationship between force on the diaphragm and the voltage applied to the electrodes. With an electrostatic force used to apply the feedback a non-electrostatic method needs to be employed to detect the motion of the diaphragm. Optical interferometry is well suited to this.

A silicon condenser microphone diaphragm has been built with two interdigitated electrodes. One is used to measure the displacement relative to the backplate in the conventional way and the second is fed with an amplitude modulated carrier signal with a carrier frequency far above the audio-frequency range which is adjusted to minimise the displacement of the diaphragm. As the force feedback principle eliminates the diaphragm impedance from the properties of the transducer this method would eliminate the problems of reproducibility between batches of micromachined transducers and would probably improve the yield.

An accelerometer has been built on similar principles except that the feedback signal is digital, consisting of pulses of fixed amplitude and duration but variable repetition rate. The feedback system adjusts the repetition rate to minimise the displacement of a mass. The repetition rate is thus proportional to the acceleration and the transducer has the unique advantage that it gives a digital output.

The force feedback principle has much to offer acoustical transducers from gains in dynamic range and frequency response to the prospect of a digital output. For the future of measurement standards for acoustics the principle has even more to offer. All the transducers reviewed so far have responded to displacement and the users assume that the mechanical impedance of the diaphragm can be accounted for in the calibration of a transducer so that it can measure pressure. Force feedback transducers respond to the force on the diaphragm and give an output proportional to that force independent of the mechanical impedance of the diaphragm. This has great potential for building acoustic transducers with good stability to temperature and ageing effects and particularly good potential for a new way of realising the primary standard for sound pressure in air traceable directly to forces derived from electrical standards.

2.7.1 UK access route

The force feedback principle has been developed mainly at Reading University for use with studio microphones. Development aimed at metrology will not progress without specific funding.

2.7.2 Relevant papers

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Tranducers'93, Yokohama, Japan

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UATG Acoustic & Optic Sensors Seminar, Southampton

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Proc IOA **8**, part 6

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The Optical Microphone - Fact or Fiction.
Proc IOA**11**, Part 7, 277-287

van der Donk A G H, Scheeper P R, Olthuis W, Bergveld P, 1992.
Amplitude-modulated electro-mechanical feedback system for silicon condenser microphones.
J Micromech, Microeng. **2**, 211-214

2.8 DIGITAL MICROPHONES

During our interviews, manufacturers of acoustical instruments expressed a desire for microphones with digital outputs for integration into their sound level meters. There were rumours of work being done on such devices but little hard evidence could be found.

A digital microphone is an attractive idea. Sound level meters have moved from analogue to digital progressively over the last two decades. Initially only the displays were digital but now on modern instruments only the transducer and preamplifier remain analogue.

Manufacturers[18] claim that "50% of the cost of a Type 1 digital sound level meter is the microphone" and that "the long term main drive to reduce the user cost will be the development of a true all digital microphone". However the principles on which such a transducer would work are not being discussed openly. The closest that this survey has found is the force feedback accelerometer described in Section 2.7.

It is difficult to guess how close such a device may be. Whenever it comes to market it will appear quickly and be integrated into a radical new sound level meter. Users, competitors and those required to calibrate such devices will get little warning.

3 FUTURE REQUIREMENTS

3.1 REQUIREMENTS IDENTIFIED IN THE SURVEY

The views expressed by the respondents to the survey varied widely. Even amongst a narrow group e.g. sound level meter manufacturers, some replied that current transducers were sufficient for their needs and that they could foresee no circumstances in which they would need to adopt alternative technologies, while others replied that they were actively commissioning research into new transducer technologies and hoped to see them incorporated into their instruments on a short timescale. The variation in replies is probably indicative of the personalities of the respondents and the positioning of their companies within the market rather than any true indicator of future trends. With such a small sample and such a varied constituency, any detailed statistical analysis of the replies would serve little purpose. Instead this section will summarise some of the comments made by respondents on the technologies that they had studied and had considered implementing.

3.1.1 Measurements in air

In general, respondents wanted various improvements to current in-air acoustic transducers. Improvements in stability, robustness and reliability, increases in bandwidth, miniaturisation, mass fabrication and so decrease in cost; all were mentioned as desirable. However, more specific improvements were also sought.

Microphones in air in general were considered satisfactory for current usage. However, users would ideally like to see lower intrinsic noise levels, greater dynamic range and increased sensitivity along with increased bandwidth and stability. Similarly, users of piezoelectric transducers would like to see improvement in sensitivity of the transducers. Miniaturisation could mean a move towards a point receiver which would be more omni-directional (a benefit for measurement purposes). Higher power transmitters would also mean an increase in the signal-to-noise ratio, which would be desirable.

The main technological advance for measurement in air which was sought was the development of micromachined acoustic sensors. Instrument manufacturers expect these to play a significant role in the development of their instrumentation in the future. Some are currently developing such transducers while others are just dreaming of a digital microphone. They hope to achieve a significant cost reduction and improved functionality from these transducers, but none are yet considering how such devices will be calibrated.

One respondent's view of the future was that we would be looking for greater precision in all measurements. Not because human reaction would become more sensitive and place extra demands but because a prime driver in acoustical measurements is the identification and elimination of noise sources. Machines are becoming quieter, engineers have done this by quietening the major sources but in order to make machines quieter still they now have to tackle many minor sources rather than one or two large sources. This will require greater precision in identifying and quantifying sources and if sound *intensity* instrumentation can be made more accessible then it has a large role to play in this quest.

Optical techniques are used infrequently at present and are largely still under development. Users rated them as having a fair overall technical performance at present. Potential benefits of this technology are higher efficiency, increased bandwidth, a decrease in the noise and vibration floor and a lowering in cost.

Several respondents were using transducers for ultrasound in air, mostly for ranging or NDT applications. One NDT user reported that exposure to the ultrasound over several hours caused pain in the ears (even though no sound was audible) and consequently the users wore ear plugs.

3.1.2 Measurements in water

Piezoelectric and magnetostrictive materials were generally considered by respondents to rate highly as far as their overall technical performance for current usage was concerned. Their main advantage lies in the fact that their technology and limitations are very well known and appreciated. They constitute the established technology for water and continue to be developed. New materials and processing techniques in these areas, including improved cutting technologies and electronic shielding, tend to have an incremental rather than revolutionary impact. General improvements in cost, repeatability and beam forming characteristics are sought, as is greater bandwidth; although a narrow bandwidth is favoured for accurate measurement over short distances and for flow assessment. Broader application will bring challenges to their calibration in a number of areas and respondents identified the following:

• Miniaturisation is a key requirement to obtain greater spatial resolution through the use of higher frequencies. This will enable the examination of fine structures such as skin, and the production of high-density transducer arrays. Also, miniaturisation is essential for some biomedical applications, such as inter-arterial imaging. Such transducers will be capable of transmitting and receiving shorter pulses (i.e. broader bandwidth) whilst being less directional. More sensitive materials will be needed for smaller elements to maintain a suitable signal-to-noise ratio. Small elements are less disturbing to the field being sensed.

• There is a need for transducers (both sources and receivers) to be calibrated under the environmental and coupling conditions in which they will be used. Transducers which operate in hostile environments are being developed. Non-contact optical techniques lend themselves to this sort of application, however these are in developmental stages at present. Piezoelectric materials which operate, and can be calibrated, at elevated temperatures (100 °C - 200 °C) are sought for NDT in industry. Similarly a need to calibrate piezoelectric materials for operation at high static pressure for sea-bed use was reported.

• Researchers in the food and chemical industries reported using ultrasound at powers in the range 30 - 50 kW at 50 kHz to produce chemical changes e.g. de-polymerisation. High power transducers to produce cavitation, violent motion and microstreaming effects efficiently are also sought. Magnetostrictive transducers have advantages for such applications; calibration at very high powers will provide challenges.

• Respondents developing probe devices with an omni-directional response indicated that there would be a need for calibration of these devices at a range of angles.

• Those involved with medical ultrasound reported a need for transducers which are robust enough to be used at high acoustic pressures, up to 100 MPa, for detecting lithotripter fields.

3.1.3 Requirements common to measurements in air and water

• Calibration of two-dimensional arrays, which may be large scale, will present challenges especially if elements must be calibrated individually. Element to element sensitivity variation will have to be controlled and elements will have to be phase matched. Acoustical holography is an area of growing interest which will rely on these techniques, presenting challenges both to transducer and signal processing technologies.

• Some respondents expressed an interest in the development of `smart' materials, which can operate anechoically by radiating in antiphase.

• Cost is always a consideration. For example airborne ultrasound transducer arrays are used for robot `vision' because of their ease of signal processing. If the transducer costs were too great then a video camera would be used instead.

• In general, ease of calibration (by the user) is considered to be important.

• In addition to the transducer technologies themselves, improved methods of data analysis and signal processing are sought.

3.2 HIGH IMPACT TECHNOLOGIES

After studying over 100 papers and interviewing over 50 people seven separate areas of likely advances in acoustic transducers were identified:

- Condenser microphones
- Capacitive transducers for ultrasound in air
- Piezoelectric materials
- Magnetostrictive materials
- Optical transducers using fibres or interferometry
- Micromachined transducers (either capacitive, piezoelectric, piezoresistive or optical)
- Force-feedback microphones

Having regard for the likely impact of these technologies on the future development of the national measurement system for acoustics, four areas have been chosen for inclusion in the strategy to be recommended:

- Capacitive transducers for ultrasound in air
- Optical methods
- Micromachined capacitive transducers
- Force-feedback microphones

The other technologies were not chosen because condenser microphones were considered mature technology and unlikely to develop fundamentally, and developments in materials were similarly thought to bring only incremental improvements to existing technologies rather than present new fundamental opportunities to metrology.

4 STRATEGY

The transducer (source or receiver) is central to acoustical measurements and hence its calibration is critical. Transducers must be calibrated either by an absolute method, where the sensitivity is determined by measurements traceable to basic measurement standards, or by comparison with another transducer that has already been calibrated. The transducer must be designed to allow it to be calibrated. If this is not done then measurements become anarchic, separated from any relationship with measurements in other disciplines and often lacking any relationship to similar measurements made with slightly different equipment. An example of this can be seen in the field of non-destructive testing by acoustic emission where the properties of the transducer are neglected by international agreement.

For a transducer to be calibrated by an absolute method, an acoustic quantity of known value can be applied to it, as for example in the pressure calibration of a microphone using the laser pistonphone[19]. Alternatively, if the operating principles of the transducer are well understood, there may be a fundamental method such as that based on the reciprocity principle[20]. If a particular transducer cannot be calibrated by an absolute method then it must be designed so that it can be compared with a transducer that can be calibrated by an absolute method and the development of the latter transducer will be essential to the success of the former.

Therefore in developing a strategy for the application of new transducers to the national measurement system, three questions must be asked:

- Does the transducer, or new technology, offer significant advantages to allow new measurements to be made which will improve industrial competitiveness or health and safety?

- If so, can the new transducer be calibrated by comparison with existing acoustical measurement standards?

- If not, is the transducer potentially capable of being calibrated by an absolute method? Alternatively, can an absolute transducer be designed which will allow the transducer to be calibrated by comparison?

4.1 CAPACITIVE TRANSDUCERS FOR ULTRASOUND IN AIR

No limits on the exposure of humans to airborne ultrasound exist in Europe though there are recommendations in other countries[21] and internationally[22]. The existing recommendations suffer from a lack of suitable measuring equipment - while they recommend the use of a sound level meter or microphone system with a linear filter they recognise that there are no instrument performance standards or measurement standards that apply above 20 kHz. Studies of the effects of airborne ultrasound will be inconclusive while there is no consistent measurement standard between different studies, and until consensus is achieved on the effects on humans no limit can be anything but arbitrary.

The recent development of wide bandwidth transducers for ultrasound in air is promising. Although they are being developed primarily as NDT transducers they could be used for measurement purposes if they prove to be stable and can be calibrated. As the transducer technology becomes available then the National Measurement System should investigate methods of calibration so that, in time, traceable measurements of airborne ultrasound become possible and rational limits on human exposure can be set. A start on this is already planned in the current Acoustics Programme. As the transducers are similar to condenser microphones then it may be possible to adapt the free-field reciprocity system at NPL to work with these transducers.

To promote this aim NPL should encourage the development of the transducers, particularly encouraging the developers to consider the properties of the transducers which will make them suitable for measurement. NPL should co-operate with the developers by offering to characterise the devices while developing the calibration techniques.

4.2 OPTICAL METHODS

4.2.1 Optical fibre sensors

As outlined in Section 2.6, optical fibre sensors are very likely to lend their key advantages (in terms of size, immunity to interference and bandwidth) increasingly to measurements of acoustic fields *in vivo* or in hostile environments, or where remote sensing is necessary. The calibration of such acoustic sensors should be explored at this stage to facilitate the application of this technology. The development of such sensors themselves, specifically for calibration purposes, should fall within the scope of this research. The optical techniques discussed below could play a significant role in such an investigation.

4.2.2 Measurement of acoustic displacement by interferometry

Optical means are already utilised by NPL in a service for the calibration of acoustic fields in the range 0.5 - 20 MHz which is supported by the NMS. Currently the primary standard for hydrophone calibration comprises an optical interferometer which is sensitive to the absolute displacement of a pellicle membrane placed in the field. There will be a need to improve the current displacement measuring interferometer because of the increased use of high frequency ultrasound in medical imaging at frequencies of 20 - 60 MHz, and the consequent need for hydrophones calibrated in this range. The current interferometer is limited by its noise performance.

4.2.3 Measurement of acoustic particle velocity by interferometry

Under a strategic research project at NPL an optical interferometer system has been developed to determine the absolute particle velocity of an acoustic field directly, with a bandwidth of 100 MHz. The Michelson type interferometer has a long path-difference geometry and a pellicle membrane placed in the acoustic field is interrogated remotely by a probe beam. Advantages of this interferometer over one which is sensitive to displacement are that the data are related directly to the acoustic parameter without need for differentiation and fringe counting is not required. Very high velocities (up to 100 ms^{-1}) can be measured and the method is applicable to acoustic fields greater than 100 MPa, which are destructive to conventional hydrophones. The system will therefore have a unique capability. It is in the final stages of commissioning and is expected to form the basis of a calibration service. This commissioning is being supported under the current NMS Acoustics programme.

We believe that an optical fibre sensor for insertion *in vivo* could be developed to provide information as to the high acoustic pressures within a patient during lithotripsy treatment (destruction of renal calculi by acoustic shocks). Such a programme of research could benefit from work currently being carried out at NPL under a Strategic Research Project on optical techniques for acoustical metrology.

4.2.4 Determination of two-dimesional acoustic pressure distribution using optical diffraction tomography

Although ODT is an interesting area of research it is complex and expensive, and not likely to meet the needs of industry on a large scale by current estimates. Further disadvantages of the method are its reliance on cylindrically symmetric fields and its inapplicability to non-linear fields. It is recommended that the development of this technique should be monitored but that at precent the UK National Measurement System should not attempt to implement it. If a need does arise in the future which can be satisfied by this method then access to the existing facilities should be sought through Euromet.

4.3 MICROMACHINED CAPACITIVE TRANSDUCERS

Micromachined transducers are being used in hearing aids and in the control loop of sound calibrators. They will soon be used in Type 2 sound level meters where they will offer a cheaper alternative to traditional microphones. As production techniques improve they will be used in a wider range of audio equipment and sound measurement equipment.

A particular area where they will be used is in arrays combined with sophisticated signal processing to provide dynamic control of directionality. Arrays may also be used in sound measuring equipment for source location or to determine the type of field that the instrument is exposed to (e.g. indicating how diffuse or reactive it is). The signal processing for these applications requires that the sensitivity and phase response of each element is known. Modern signal analysers such as those using maximum-length sequence analysis to characterise loudspeakers also need knowledge of the phase response of the measurement microphones. Some national standards laboratories have extended their calibration methods to include the phase response of measurement microphones[23]. A similar requirement exists for underwater transducers which are frequently used in arrays. It is recommended that as the primary standard for sound pressure (both in air and water) is developed at NPL then an ability to extract phase information should be included so that future demands for phase information on transfer calibrations can be accommodated.

As micromachined transducers improve they will be used on an increasing variety of acoustical instrumentation. Initially the instruments will be calibrated in the free field by comparison with laboratory standard microphones. Sound calibrators designed for use with these instruments will have to be calibrated using an instrument which itself is calibrated in a free field. This will result in uncertainties of more than 0.2 dB on the calibration of a sound calibrator. As micromachined transducers get used on precision instruments then a calibration uncertainty of 0.2 dB on a sound calibrator will not be acceptable. If acoustical instruments started to use transducers based on the force feedback principle, or optical or digital microphones, then the calibration problem would become more difficult still.

The pressure calibration of micromachined transducers either by comparison with existing microphones or by reciprocity would be difficult. In coupling these microphones to small cavities the uncertainties on the internal volumes of those cavities would make the calibration useless. To maintain uncertainties at their current levels a new method of realising the primary standard of sound pressure will be required.

An absolute calibration method could in principle be based on the radiation pressure from a laser. When an electromagnetic wave is incident on a surface it delivers a pressure which is simply related to the intensity of the wave, and calibration of the intensity of a laser and knowledge of the reflection coefficient of a diaphragm would allow the pressure to be calculated. The laser beam would consist of very short pulses allowing the impulse response of the transducer to be determined and restricting the heating effect of the laser beam. Unfortunately the intensity required to generate a detectable pressure is very large. If the beam of a typical class IIIb laser (giving 30 mW) was expanded to cover a 1 mm^2 diaphragm the pressure would be equivalent to 14 dB SPL. A 10 W laser would be required to generate a pressure equivalent to 65 dB SPL. The cost and safety requirements of working with such powerful lasers would be prohibitive at the current time.

The calibration of micromachined transducers will require the development of absolute transducers of similar size to the micromachined transducers. Such a method may be developed from the principles of the force feedback microphone.

4.4 FORCE FEEDBACK TRANSDUCERS

The force feedback principle has much to offer acoustic transducers: independence from the mechanical properties of the diaphragm, improved stability and perhaps even active control of the transducer characteristics. The most successful implementations so far have used electrostatic force feedback and optical detection methods as this combination eliminates any cross talk between the sensing circuit and the feedback circuit. Unfortunately the electrostatic feedback requires two grids, one each side of the diaphragm, if the output voltage is to be proportional to the sound pressure. (A single grid would give a voltage proportional to the square root of the pressure). This is acceptable in a working standard transducer which usually has a grid in front of the diaphragm for protection purposes already, but presents a problem for laboratory standard transducers which need an exposed diaphragm[24]. Thus working standard force feedback transducers would need to be calibrated by comparison with a primary device.

The force feedback principle could be applied in a different way to build a primary device. If the calibration signals were restricted to single frequencies of very long duration then having a voltage that was proportional to the square root of the pressure would not pose a problem and the feedback system could even be manually adjusted. Such a device would consist of a diaphragm, exposed on one side to the sound pressure and subject to an electrostatic force on the other. An optical method would be used to detect the motion of the diaphragm. The electrostatic force would be adjusted until the diaphragm motion ceased at which point the pressure from the electrostatic mechanism and the sound pressure would be equal and could be determined from measurements of voltage and capacitance. Free field corrections for such a device could be derived theoretically because the diaphragm would be stationary and present an infinite acoustical impedance.

It is proposed that a feasibility study should be commissioned to investigate the practicality of such a device. Many questions need to be answered, for example:

- What type of diaphragm should a prototype have? Is experience with traditional metal diaphragms desirable or could the first prototype use a micromachined diaphragm?

- Is it possible to eliminate the motion of the diaphragm at all points simultaneously or will the feedback only minimise the motion?

- What uncertainties could be expected from the electrostatic measurements?

- Which optical detection methods would be most appropriate?

- What sensitivity and frequency response would the device offer?

- What would the free-field to pressure sensitivity corrections be?

The feasibility study will require a range of expertise unlikely to be found in one organisation and would be most efficiently done in cooperation with some of the researchers identified in the course of this study. The aim of the feasibility study would be to produce a specification for a prototype force feedback microphone, for use as a primary standard of sound pressure.

Potentially, such a device would offer the following advantages over the existing primary standard:

- A small transducer which could be used to calibrate small microphones by a comparison method.
- A small sensing area which would reduce the disturbance caused by introducing the device into an acoustic field. Any remaining disturbance could be analysed theoretically and corrected for.
- An increase in the frequency range, perhaps even to 1 MHz.
- Traceability to base SI units by a more direct route, through electrical quantities, eliminating uncertainties due to the properties of the air (speed of sound, density, viscosity, etc).
- A sensitivity independent of atmospheric pressure.
- Excellent long term stability.

5 RECOMMENDATIONS

We recommend that:

1. Approaches should be made by NPL to those organisations developing capacitive transducers and micromachined silicon transducers, to cooperate with them on the characterisation of these devices at ultrasound frequencies in air.

2. Optical sensing methods, in particular for high power/cavitating ultrasound fields in water, should be developed and maintained, including the existing work on the NPL velocity interferometer.

3. Calibration methods for measurement microphones and underwater hydrophones should be extended to include phase information.

4. A feasibility study into the development of a primary standard for sound pressure in air based on force feedback principles should be conducted.

Recommendations 1 and 2 can be adopted within the current NMS Acoustics programme at NPL. Recommendation 3 could be part of the next programme due to start in 1998. Recommendation 4 could also be part of the next programme, but if supplementary funding enabled the feasibility study to be conducted next year then the findings could inform the development of the next programme allowing more certainty in defining the work to be done to exploit this technology.

The study has focused on a strategy for *new* transducer technologies and consequently some potentially significant incremental improvements in transducers have not formed part of the final strategy. Such incremental improvements include those in sound intensity probes and small area hydrophones or needle probes. Nor has the study considered developments in measuring instrumentation beyond the transducer, such as sound intensity processors or the NPL Ultrasound Beam Calibrator. Work in these areas continues and recommendations on the future work necessary in these areas will form parts of other studies.

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