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REPORT

An investigation into the establishment and assessment of a test facility for the calibration of acoustic emission sensors

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AN INVESTIGATION INTO THE ESTABLISHMENT AND ASSESSMENT OF A TEST FACILITY FOR THE CALIBRATION OF ACOUSTIC EMISSION SENSORS

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ABSTRACT

This report documents the results of a study into the establishment and assessment of a reference test facility for the calibration of acoustic emission sensors. It has been shown that sensor calibration can be achieved in compressional wave mode by through-transmission measurement using a well-characterised glass test block. A new laser interferometer of high sensitivity and excellent noise performance has been acquired and it has been shown that laser interferometry provides an effective method of making non-contact measurements of surface displacement for calibration purposes.

The calibration method chosen for the work relied on the transmission of tone bursts of relatively long duration through a glass test block. However, it has been demonstrated that given the limited size of the block, and the resonant nature of the AE sensors available for calibration, this method can be sensitive to the signal processing methods chosen for analysing the calibration data. Calibration of resonant sensors at lower frequencies would require a larger test block, if measurement uncertainties are not to become unacceptably large but calibration of wide bandwidth sensors is likely to prove much less problematic.

The report also reviews existing international standards in the field of acoustic emission and describes calibration methodologies adopted by national measurement institutions and other organisations with an interest in acoustic emission sensor characterisation. In addition, it provides advice and guidance on calibration and testing methodologies for users of acoustic emission sensors.

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CONTENTS

1 INTRODUCTION

1.1 BACKGROUND

Acoustic emission (AE) refers to sounds, in the form of acoustic and ultrasonic energy, emitted from either a process or material which can provide further information about that process or material. AE differs from other non-destructive testing (NDT) techniques in two main respects: firstly, the energy is released from within the test object itself; and secondly, AE is capable of detecting dynamic processes associated with the degradation of structures, such as crack growth or plastic deformation. AE makes use of the fact that localised discontinuities will appear long before a structure fails. Monitoring of items such as crack growth gives the maintenance engineer a very useful tool. It prevents the need for unnecessary and expensive early shut-down of plant, as well as providing the means to minimize expensive, and often dangerous, failures. Recently interest has increased in the use of AE as an in-service condition monitor and as an on-line process monitoring technique. Examples cover a wide spectrum, from monitoring of large pressure vessels, storage tanks, and large structures such as bridges and aircraft structures, to studying tool wear and compositions of liquids.

Although AE has been used for many years, the last ten years has seen increased computing power enable advances in signal processing such that the reliability of the AE technology is now recognised by a wider range of industries. Furthermore, the need for quality control at the manufacturing stage and during in-service testing is encouraging the issue of traceable measurements to be addressed.

1.2 THE PROJECT

This collaborative project begins to address the need for traceable calibrations of AE transducers. The project covers the development of equipment for primary calibration of acoustic emission sensors, specifically in the application area of detection and location of discrete microfracture events that accompany stable crack growth in metals, due to fatigue and stress corrosion.

A subsurface micro-fracture event accompanying crack growth is “explosive” in nature, producing transverse and longitudinal stress waves which radiate through the material. The magnitude of such cracks is typically of the order of 30 to 300 μm, and the duration of the event is typically 0.1 μs to 1 μs.

The sensors used in acoustic emission monitoring are usually of the narrow band (resonant) type. The bandwidth is typically one octave, with the primary resonance occurring around the centre of the band (typically in the 100 kHz to 400 kHz range). The frequency response of specific sensor/preamplifier combinations depends critically on the impedance of the sensor element, the sensor cable and the preamplifier. Therefore these must be treated as a single unit for calibration purposes as, in multi-channel source location applications, small differences in the frequency response and sensitivity of the sensors can be detrimental to source location accuracy.

An informative overview of the application of acoustic emission to the monitoring of engineering structures, including arguments in support of the need for the calibration of sensors, is provided by Rogers (2001).

1.3 THE PROJECT PARTNERS

Three UK companies have already been working as a consortium to produce a new generation of intrinsically safe, multi-channel acoustic emission monitoring systems for the remote detection, location and classification of stable propagating cracks. These companies believe that for their instrumentation to be widely accepted it is important for them to consider the traceability aspect of the sensor calibration, and to ensure that it is based on reliable physical principles. For this reason the consortium, represented by Lloyd's Register of Shipping and Airbus UK approached NPL, resulting in the collaborative project described in this report. They envisaged that NPL, as the UK's national metrology institute, would take a leading role in considering, developing and advising on the proposed method of sensor calibration and eventually ensuring that quoted sensitivities are traceable to national standards.

Lloyd's Register of Shipping and Airbus UK have therefore been working with NPL to establish a reference test facility for the calibration of AE sensors. In addition, a small company that specialises in the manufacture of laser interferometers, Photometric Consultants Ltd, has developed a laser interferometer to measure stress-wave displacement perpendicular to the measurement surface for use in the project.

The particular application areas for Lloyd's Register include transportation, shipping, energy generation and off-shore installations such as oil rigs. Rogers (2001) sets out case studies of acoustic emission applications which are of interest to Lloyd's Register: fatigue crack detection in the node joints of off-shore structures, safe life fatigue testing of aircraft wing elements, stress corrosion cracking in steel pressure vessels, re-qualification of high-pressure gas cylinders, and condition monitoring of bearings.

Airbus UK are particularly interested in using AE techniques on aircraft structures, such as joints in wings and attachments of landing gear, initially to focus other NDT services, but in the longer term to include in-flight monitoring, with deployment of sensors during manufacture. AE also has the advantage that inaccessible areas in the aircraft can be studied without the need to disassemble parts of the structure. Airbus UK believe that acoustic emission has an important contribution to make to Aircraft Health and Usage Monitoring Systems (AHUMS). If structural surveillance techniques based on operational fatigue damage monitoring are to gain widespread acceptance by the airworthiness authorities, the ability to demonstrate that transducers have been calibrated and can perform to the required specifications is essential. Further information about Airbus's work can be found in O'Brien (1996a, 1996b, 1998).

Ability to demonstrate AE measurement as a recognised, proven technique using traceable sensors, calibrated using a reliable method based on well-founded principles, would have important financial implications for these and other companies, as well as giving advance warning of severe or life-threatening situations.

1.4 THE AIMS OF THE PROJECT

This report documents work carried out at NPL to establish and assess a reference test facility for the calibration of acoustic emission sensors. It reviews existing methods of AE sensor calibration and sets out the reasons for the method chosen by NPL and its partners. The calibration technique described here relies on the generation of longitudinal waves in a glass block using a piezoelectric transducer. The displacement of the surface of the glass block is to be detected by a laser interferometer. The output of an acoustic emission transducer coupled to the block can then be compared directly with the displacement measured by the interferometer. In this way the transducer response as a function of frequency and of a particular wave mode can be referred directly to the motion of the surface of the block. Alternatively, the interferometer's displacement waveform may be differentiated to give the velocity of the surface and the AE transducer's response can be expressed in terms of surface velocity.

The design and manufacture of the laser is described, and the acoustic and optical properties of a glass test block are described and analysed. Simulated acoustic emission sources for use in calibration systems are reviewed and reasons for the initial choice of a conical piezoelectric transducer as a source are presented. Finally, the results of test calibrations of typical narrow-band AE transducers are presented and evaluated.

Owing to the short time scale over which this project was to be completed, it was necessary to carry out three main project activities in parallel. These were the design, development and testing of a calibration system and methodology, the specification and manufacture of the Photometric Consultants' laser interferometer to meet the low noise, high sensitivity measurement requirements needed for AE sensor calibration, and the manufacture of conical piezoelectric transducers for use as acoustic sources in the planned calibration method. To make progress on the development and testing of the calibration system prior to the delivery of the interferometer and the conical transducers, it was necessary for NPL to employ an existing laser interferometer together with suitable commercially-available non-destructive testing transducers during the early stages of the project and the calibration results presented in this report were obtained with this alternative system. Following acceptance testing of the Photometric Consultants interferometer and initial measurements using conical source transducers, it seems likely that the performance of the new system will exceed that achieved in the calibrations described in chapter four of this report.

1.5 STRUCTURE OF THE REPORT

The structure of the report is as follows. Chapter 2 explains the phenomenon of acoustic emission and how it may be detected, and explains why traceable calibrations may be of benefit. It reviews existing calibration methods, defines the concept of traceability, and emphasises the differences between primary and secondary calibration methods. Finally, it sets out the approach to calibration adopted by NPL and its partners in this project. Chapter 3 gives an overview of the proposed method and discusses the importance of defining clearly the wave mode to be used in the calibration. It sets out the specification of the laser interferometer to be supplied by Photometric Consultants Ltd and gives reasons for the choice of the glass test block material and the proposed use of conical point-source piezoelectric transducers in calibrations. Chapter 4 sets out the main experimental results obtained during the study, including the acoustic characterisation of the test block, the sensitivity and noise performance of the interferometer. It also presents results of test calibrations on AE sensors.

The final chapter reviews briefly the achievements of the current project and makes recommendations for future work. In particular, it suggests how the current achievements can be developed and extended during the course of the current 3-year NPL Acoustics programme funded by the National Measurement System Policy Unit on behalf of DTI, of which acoustic emission forms an important part.

2 CALIBRATION OF ACOUSTIC EMISSION SENSORS: THEORY AND USER REQUIREMENTS

2.1 ACOUSTIC EMISSION: WHAT IT IS AND HOW IT IS DETECTED

2.1.1 What is AE?

Acoustic emission (AE) is a passive non-destructive testing (NDT) technique that has been used widely since the 1970s. Its use in modern times can be traced back to the work of Josef Kaiser (1950), who reported that engineering materials emit low amplitude clicking sounds when stressed and that these could be detected using the appropriate sensors and electronic amplification. He is most commonly associated with the "Kaiser effect" - the observation that a material does not start to re-emit AE signals until the applied stress exceeds that which the material had previously experienced. However, it was not until after his death that the technique became more widely exploited.

AE has been defined as the spontaneous release of elastic energy by a material when it undergoes deformation. A classic example of this is the initiation of a failure mechanism in a solid structure, such as a fracture releasing energy into the structure. The use of AE has steadily increased since its early use in the late 1960s and 1970s. It is now employed throughout many sectors of industry in applications that are not limited to monitoring of deformation processes. It is more accurately defined by the American Standards for Testing and Materials (ASTM) as "*a phenomenon whereby transient elastic waves are generated by the rapid release of energy from localised sources within a material, or the transient elastic waves so generated*" (ASTM E 610:1977). It follows that to monitor the energy released at the originating source, it is the resulting stress waves that must be measured. Herein lies the limitation of acoustic emission measurements. The stress waves measured at the surface of the structure depend largely on the nature of the structure and thus the propagation path of the waves themselves. Generally the term "acoustic emission", as it is commonly used, refers to the stress waves that arrive at the surface within an approximate frequency range of 100 kHz to 1 MHz. These frequencies correlate to microscopic events that often manifest themselves at the surface of a material with displacements of the order of picometres.

To understand the advantages of a technique like AE it is important to appreciate that it differs from other NDT methods in two main respects. Firstly, the AE event is not caused by the intentional injection of an acoustic signal into the component under test, as occurs with conventional ultrasonic non-destructive testing. It is thus passive by definition. Secondly AE is capable of monitoring dynamic processes associated with the degradation of structures, such as crack growth and other deformation processes. AE makes use of the fact that localised discontinuities will appear long before a structure fails. Monitoring of degradation processes gives very useful information that can allow machine/structural failures to be pre-empted and also reduces the need to shut down plant for inspection. As Rogers (2001) points out, crack growth arising from fatigue and stress corrosion is normally a slow degradation process up to a point beyond which failure may be sudden and catastrophic. Detection as early as possible during the initial period of growth is necessary, if the consequences of unexpected failure are to be avoided.

2.1.2 Classifying acoustic emission sources

From the definitions given above it is clear that sources of acoustic emission can be categorised in two ways. Sources that are explained by the classical definition are those that occur due to mechanical deformation of a stressed material. Examples of classic sources of acoustic emission in metals include crack growth, moving dislocations, and slip, twinning and grain boundary sliding in metals. In composites, matrix cracking, the debonding of fibres and the fracture of fibres can give rise to acoustic emission signals. The modern ASTM definition of acoustic emission allows for sources that result without any deformation process occurring. These non-classical or pseudo-sources are described as sources that can be detected using AE equipment that are not explained by the classical definition of acoustic emission. Pseudo-sources of acoustic emission include fluid leaks and cavitation in pipes, liquefaction, solidification, solid-solid phase transitions, friction and magnetic domain realignment.

Acoustic emission sources can be further categorised by the signals they produce, which can be either discrete or continuous. A discrete signal is produced by a single burst of energy from an AE source such as a fracture or impact. Continuous AE signals are produced by AE sources such as fluid leaks, friction or chemical processes. Most continuous signals are actually made up of sources of a discrete nature that occur so rapidly and in such large numbers that they are considered to be a continuous process. It is reasonable to state that most applications use AE to monitor classical-type sources of a discrete nature. The work reported here employs only artificial sources, as these are used to simulate real AE events to allow calibration of AE sensors or measurement systems.

As has already been mentioned, acoustic emission measurement is performed at the surface to detect the stress waves produced by an AE source within the material. To put acoustic emission in context it is important to understand the intensities of the events occurring within the structure. The energy released from a fracture source can be of an order as low as 10^{-8}J (Rogers, 1998). Of course this depends on the source, and it may be much larger. To detect the disturbance at the surface created by such a small energy release means that highly sensitive transducers must be used.

2.1.3 Transducers for AE detection

Transducers used for acoustic emission measurement are in general sensitive to surface motion normal to the surface to which they are attached. The sensitive bandwidth of the transducers has to be carefully selected such that the signal-to-noise ratio (SNR) is acceptable. Owing to the inherent difficulty of AE measurement, it is important to isolate vibration and air-borne noise. Typically, AE transducers are sensitive to frequencies above 100 kHz. Resonant transducers further increase the SNR by being highly sensitive to a very narrow frequency range which must be carefully selected depending on the application. Resonant transducers in the region 150 kHz to 300 kHz are probably the most widely used in AE applications. The highest frequencies likely to be of interest to users of AE transducers are in the range from 800 kHz to 1 MHz. Hence transducers with bandwidths which extend above this range are not normally used, to ensure that electronic noise is kept to a minimum. Electronic filtering is employed to remove any unwanted signal noise at the high or lower frequency extremes.

There are several ways in which this transduction can be achieved. The piezoelectric effect, capacitance methods and optical interferometry are common techniques used for detection of AE in industry and research. Piezoelectric devices offer the greatest sensitivity and are thus the most widely used type of transducer in acoustic emission applications. In testing the structural integrity of a pressure vessel, for example, resonant transducers are used to provide maximum sensitivity over the bandwidth of interest; they also provide pass band filtering so that noise outside the frequency range of interest is not detected. In other cases where the characteristics of the source are of interest, wideband piezoelectric transducers are used, usually with a relatively flat frequency response from 100 kHz to 1 MHz. The increased measurement bandwidth of these devices is obtained at the expense of sensitivity. When broad bandwidth measurement is of primary importance then optical and capacitive techniques are employed. Interferometers and capacitance transducers have the capability to perform very high fidelity measurements over a broad frequency range far beyond that of conventional piezoelectric transducers, often over tens of megahertz. Interferometers also provide very good spatial resolution, which is ideal when measurements of small changes in surface displacement are required. Also, non-contact allows an accurate measurement of the acoustical quantity. Both the latter techniques are, however, relatively insensitive, being orders of magnitude less sensitive than a typical AE piezoelectric sensor. Furthermore, these devices can be very delicate and are normally limited to laboratory use where measurement conditions can be controlled. Interferometers and capacitance transducers are often used to calibrate piezoelectric AE transducers owing to their flat, broad frequency response and inherent absolute measurement.

2.1.4 The Consortium's approach

The approach to acoustic emission signal measurement and classification adopted by the Consortium mentioned earlier is to deploy an array of acoustic emission transducers and to filter out acoustic emission signals which do not emanate from crack sources. They argue that stress waves arising from a crack only occur when a crack is growing and that, apart from a minimal shift due to the growth of the crack, the signal occurs at a regular interval during a duty cycle and from the same position at each time. Emissions from other sources do not repeat in the same manner as cracks. O'Brien (2002) describes this process as a phenomenological filter, which operates in the following way.

> *…To elaborate the principle of the phenomenological filter assuming that a monitored structure contains a growing fatigue crack. On the first fatigue cycle acoustic emissions will be recorded from a number of fasteners, interstitial movements, mechanical systems and air flow as well as from the crack tip. On the second cycle acoustic emissions will come from a different set of fasteners, material features, etc including emissions from the crack tip which retains its original location. On the third and subsequent cycle a similar process takes place again recording the crack tip information from its unchanged location. Of course the crack may not grow on every cycle but for a structure undergoing an organised loading plan such as a service aircraft any crack will emit signals on a regular basis from the crack tip. By a process of ranking signals that repeat in terms of location are retained and signals that do not repeat are discarded. Within a relatively short number of duty cycles, say 50 -100, a strong pattern emerges from the data indicating the presence and position of a growing crack. The use of the phenomenon of*

crack tip acoustic emissions emanating in strong bursts from the same geometric position and non-crack acoustic emissions presenting themselves in a manner that does not repeat on a regular basis forms an effective filter.

For this filtering process to work efficiently, reliable matched sets of transducers are required, whose performance characteristics are known. It is this requirement that underpins the Consortium's interest in the current project.

2.2 CALIBRATION – RELEVANT DEFINITIONS

Before we begin a discussion of the need for calibration of acoustic emission transducers, it is useful to review the definitions of the key terms, as defined internationally (BSI, 1995). The terms listed here will be in constant use throughout the remainder of this report and it is important to appreciate the exact manner in which a particular term is used.

Calibration is a "*set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards*."

A primary standard is a "*standard that it designated or widely acknowledged as having the highest metrological qualities and whose value is accepted without reference to other standards of the same quantity."*

A secondary standard is a *"standard whose value is assigned by comparison with a primary standard of the same quantity."*

A reference standard is a *"standard generally having the highest metrological quality available at a given location or in a given organization, from which measurements made there are derived."*

Traceability is a *"property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties."*

Sensitivity is *a "change in the response of a measuring instrument divided by the corresponding change in the stimulus."*

The discrimination (threshold) is the *"largest change in a stimulus that produces no detectable change in the response of the measuring instrument, the change in the stimulus taking place slowly and monotonically."*

Resolution is the *"smallest difference between indication of a displaying device that can be meaningfully distinguished."*

Accuracy of measurement is *"closeness of the agreement between the result of a measurement and a true value of the measurand."*

Repeatability is the *"closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement."*

Reproducibility is *the "closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement."*

2.3 ACOUSTIC EMISSION SPECIFICATION STANDARDS

2.3.1 General

Since the 1980s there has been a rapid development of codes of practice for acoustic emission testing. Rogers (2001) sets out a list of the codes currently governing acoustic emission measurements. These codes arise mainly from two sources, the American Society for Testing and Materials (ASTM) and the Codes subgroup of the European Working group on Acoustic Emission, which has now been superseded by the Commission for European Norms Technical Committee 138 (non-destructive testing) Working Group 7 (CEN/TC138/WG7). The codes not only cover generic topics such as terminology, general principles of acoustic emission, and the characterisation and testing of AE equipment, but also provide much application-specific advice. Most of the standards discussed below concerning measurement and calibration have been mirrored in the countries that regularly use acoustic emission, and as such can be considered to be internationally accepted standards.

However, it is clear that AE practitioners themselves do not seem to have adopted consistent practices when it comes to the question of transducer calibration. Investigations by NPL suggest that many users consider the ‘check’ that they perform prior to measurements using the well-known pencil lead break (the Hsu-Nielsen source, as it is commonly known) as a calibration. In reality, it appears this is often used simply as a check that the equipment is working, that the amplitude of the signal is as expected, and that the signal-to-noise ratio is suitable to continue testing. Those AE users who had some form of calibration ‘certificate’, which usually appeared to be to a manufacturer’s specification, very rarely used any sensitivity figure in their measurements, other than to be sure that the sensitivities of different signal channels were comparable. Users also seemed uncertain of the actual parameter they were measuring, which in many cases was not important to them, as they were only making comparison measurements. The concept of traceability was recognised only by those users wishing to make absolute measurements.

It therefore appears that there is a need to adopt a consistent approach to the characterisation of acoustic emission transducers, which is accepted and understood by all practitioners, and which relates transducer performance and sensitivity to defined, reproducible quantities. In addition, it should allow comparisons between different transducers, as an aid to transducer selection. Of course, for some applications it may not be necessary to adopt such a systematic methodology. However, if one is concerned with the simultaneous use of sets or groups of transducers to locate precisely the source of an AE signal, or if one is interested in predicting the magnitude of a crack which gave rise to a particular signal, well-characterised, calibrated transducers will be an essential requirement. In the light of these observations it is interesting to review the range of calibration methods, both primary and secondary, which already exist.

2.3.2 The existing standards

2.3.2.1 Absolute calibration

The frequency range of fracture events is in general wide, with crack sizes in the region 100 µm to 1 mm expected to produce stress waves predominantly in the frequency range 150 kHz to 1.5 MHz, which is the normal frequency range for acoustic emission measurements in metals. In many applications of AE, the form of the AE signal and the detailed effect of the propagating structure and the wave modes it can support and allow to propagate are often unknown, and the actual transducer output signals will depend significantly on the positioning of the transducer on the propagating structure. This structure may well change its form with temperature variation and with the physical changes which give rise to the AE signals. In addition, the AE transducer sensitivity is subject to variation as a result of damage and ageing.

The current standards and calibration procedures are important to the users of acoustic emission but do not tackle the need for quantitative measurement of the acoustic emission source. The inadequacies of the current approaches in providing quantitative information are summarised below, and show that outside the scope of this project there is a need to consider a different approach to the problem of absolute measurement of acoustic emission.

Confidence in any measurement can only be provided if it is performed in accordance with a suitable quality assurance process. Acoustic emission is no different. Unless specified guides and standards are followed the measurement becomes ambiguous. Acoustic emission can be particularly ambiguous, owing to the fact that the measurement is made after propagation through an undetermined medium. Changes to the medium or to the environment surrounding the medium can cause unpredictable variations in the measurement. Industries that use acoustic emission therefore need approved guides or accepted standards to follow in preparing and making the measurement in order to be able to use the results to certify components or products.

The major users of acoustic emission have been the USA, Japan and, more recently Europe, which has made widespread use of acoustic emission as a non-destructive testing technique. The USA and Japan were thus first to see the introduction of accepted standard codes for the performance tests of measurement equipment and measurement procedures. The American Society for Testing and Materials has been the largest contributor to the development of standards and codes in this area since 1980. The guides produced fall into two main categories: (a) those outlining procedures to follow in characterising AE sensors or calibration of equipment used in the measurement of AE, and (b) those concerned with the procedures to be followed in making a measurement.

An additional standard is a guide of standard definitions of terms relating to acoustic emission (ASTM E 610-77). This standard is produced by ASTM and is referred to in all other ASTM guides. More recently the European Committee for Standardisation (CEN) introduced a more comprehensive but otherwise similar standard (DRAFT prEN1330-9). Many terms used in acoustic emission are unique to the field of AE and others may sometimes differ from similar ones used in other fields.

The characterisation and calibration of equipment used in the measurement of acoustic emission is outlined in three main standards produced by ASTM which mirror standards more recently produced by CEN. Following work done by Hsu and Breckenridge (1981) on the frequency characterisation and calibration of acoustic emission sensors, a standard was produced by ASTM outlining a method for primary calibration of acoustic emission sensors (ASTM E1106-86). The standard was published in 1986 and re-approved in 1992. The ASTM guide has been mirrored in an international standard (ISO 12713). The primary calibration of acoustic emission sensors is discussed in depth later in this report.

2.3.2.2 Relative performance checks

Depending on use, an absolute calibration of the AE sensor may not be required. In some applications a simple comparison of the responses of sensors, or even just a check for any degradation in a sensor's performance may suffice. In these cases a different procedure can be followed. The ASTM standard guide (E976-94) implemented in 1994 describes the procedure for determining the reproducibility of acoustic emission sensor response. The specific reasons for checking a sensor's response and thus the conditions for the use of this guide are stated as being:

- checking the stability of its response with time;
- checking the sensor for possible damage after accident or abuse;
- comparing a number of sensors for use in a multi-channel system to ensure their responses are adequately matched;
- checking the response after thermal cycling or exposure to a hostile environment.

The comparisons or tests described are all relative. However, a key recommendation is the use of a non-resonant test block. The design is essentially a cone with the top milled off at an angle which is not parallel to the base. The rationale for such a block is that it supports no orders of single-frequency standing waves. Several sources are described as being suitable for sensor characterisation; the sources are both continuous and discrete. The continuous sources recommended are a gas jet on the surface of the test block and a white noise generator driving an ultrasonic transducer. The discrete sources considered suitable are the pencil lead break on the surface of the block and an ultrasonic transducer driven with a pulse. The guide then goes on to describe the requirements for the recording or analysing equipment, including recommended cable lengths. Since the determination of repeatability is of a relative nature it is important that all equipment used in the acquisition of the data is identical between tests.

2.3.2.3 Instrumentation

The instrumentation used in the measurement of acoustic emission is the subject of a separate ASTM guide (E750). This guide, first produced in 1980 and re-written and submitted in 1988, was re-approved in 1993. Aspects of testing instrumentation for acoustic emission are described covering bandwidth, frequency response, gain, noise level, threshold level, dynamic range, signal overload point, dead time and counter accuracy. Characterising acoustic emission equipment is also covered in a more recent and thorough two-part CEN guide (DRAFT prEN 13477-1 and DRAFT prEN 13477-2).

2.3.2.4 Coupling

In the measurement of acoustic emission, the coupling of the sensor to the structure can be a major source of poor repeatability. ASTM therefore produced a standard practice guide for mounting piezoelectric acoustic emission contact sensors (E650). The standard was approved in 1978 and covers issues to be considered when bonding a sensor for measurement. There are three main aspects: the structure preparation prior to mounting of the sensor, the couplant selection, and the mounting fixture selection. Structure preparation is highly important, the surface quality or the presence of other layers, oxide or paint for example, can affect the acoustic emission signal greatly. On a clean surface it is then important to attach the sensor each time with a consistent pressure and a couplant that will not degrade with time. This guide is referred to frequently in other procedural guides on the measurement of acoustic emission.

2.3.2.5 Application-specific standards

Codes of practice have been produced in association with nearly all applications of acoustic emission measurement that are performed on a large scale. The largest use of acoustic emission is in applications where structures undergo stress. These include pressure vessels and pipelines. For this type of application ASTM has produced a guide entitled ‘Standard practice for acoustic emission monitoring of structures during controlled stimulation’ (E569-85). This guide covers the standard procedure for testing structures by a cycle of loading whilst monitoring for acoustic emission activity up to a pre-defined load. It is accepted that the methodology followed does not allow the severity of a defect to be assessed. The use of other NDT methods are advised, usually ultrasonic, to further assess the severity of defects found during the controlled stimulation.

Most of the guides used in the field of acoustic emission are related to procedures to be followed for specific application areas. These guides have been produced for individual needs to suit the particular application in hand and as such are not specifically internationally agreed documents.

2.4 CURRENT SENSOR CALIBRATION TECHNIQUES

2.4.1 General

Acoustic emission measurement systems are passive systems that respond to a source of unknown origin and unknown quantity. It is not possible for the measurement system to quantify the strength of the source. This has led to a lack of traceable measurement in the field of acoustic emission measurement and has made the comparison of results between different measurement systems or even different measurement conditions very difficult. This problem has largely been ignored and to date calibration methods only measure the response of a sensor to a known surface displacement. Traceable sensor calibration is currently performed largely by the USA's National Institute of Science and Technology (NIST), and the Nippon Steel Corporation (NSC), Japan.

2.4.2 The NIST method

Step-force sensor calibration is the method favoured by NIST and is outlined in an ASTM guide (E1106-86). It was first proposed by Breckenridge et al (1991). It uses a standard reference capacitance transducer with a known step-force AE source on a steel transfer block. The sensor to be calibrated is placed on the steel transfer block on the same surface as a reference transducer, opposite and equidistant from the source. The test block itself is a 0.9 m diameter, 0.43 m long cylinder. The step-force is generated by the fracture of a glass capillary.

The response of the sensor being calibrated to the step-force source is then compared with the reference transducer, which measures the surface displacement due to the elastic surface waves. The displacement at the reference transducer can also be calculated using elastic theory. The surface motion on the transfer block, determined using either technique, is the free motion of the surface and not the loaded surface displacement, under the transducer being calibrated. The loading effect of the sensor being calibrated, therefore, affects the measurement being made and thus becomes part of the calibration.

Step-force calibration can also be applied to the calibration of bulk waves by the use of ‘through calibration’ as opposed to ‘surface calibration’. Through calibration requires a thick plate with both the sensor being calibrated and the reference transducer on the opposite side of the plate to the glass capillary source. Both methods result in the transducer being calibrated in terms of displacement, in units of volts per metre.

The breaking of a glass capillary closely approximates the ideal point force step function that is required to determine the displacement, as a function of time, at the transducer, using elastic theory. The capillaries used are standard capillary tubes 0.2 mm in inside diameter, with a wall thickness equal to the bore size. The capillary is laid horizontally across the steel transfer block separated by only a glass microscope slide cemented to the surface of the block (to protect the steel surface from damage). The force is applied by a loading screw via a 2 mm solid glass rod laid perpendicularly across the top of the capillary tube. The applied force at which the glass capillary breaks is measured using a lead zirconate titanate (PZT) disc element mounted within the tip of the loading screw. It should be noted that the source of the stress-wave produced by the fracture of the glass capillary is not from the fracture itself, but is a result of the sudden release of force.

The ideal properties for an acoustic emission transducer are defined by Scruby et al (1978) to be:

1. sufficient sensitivity to detect emission of the energy normally encountered in acoustic emission tests;
2. sufficient bandwidth to cover the full frequency range of the emission source;
3. reproducibility, i.e. its transfer function must be independent of the test;
4. a design which is compatible with most common testing configurations;
5. to be amenable to calibration so that the relation between the input signal, in terms of absolute surface displacement or velocity, and the output signal can be determined.

A reference transducer, such as the capacitance transducer used in this calibration, ought to be as close as possible to this description of an ideal AE transducer. The sensitivity of a capacitance transducer is typically about an order of magnitude less than that of a piezoelectric device. The frequency response is relatively flat over the usable bandwidth, but that bandwidth is itself not wide enough to ensure complete coverage of the range of all AE sources. The reproducibility of the capacitance transducer is good compared to that of a piezoelectric device, owing to the fact that it is non-contacting and therefore suffers from no coupling inconsistencies. Its reproducibility is dependent, however, on the air gap between the capacitor plates and, since the calibration block forms one of the plates, the surface of the block and the sensor must be polished to a mirror finish with an air gap of about 4 μm. The design of the capacitance transducer does not have to be compatible with most common testing configurations as it is used purely as a reference transducer. The rise time of the capacitance transducer increases with increasing plate area owing to the path differences of waves arriving at the centre of the plate and the circumference (Scruby and Wadley, 1978), which therefore decreases the bandwidth. The bandwidth achieved by NIST is around 5 MHz with a very flat response over the useful 100 kHz to 1 MHz range, using a 100 V bias voltage, 4 μm air gap using a more complex cylindrical capacitance transducer set-up (Breckenridge and Greenspan, 1991).

The calibration facility at NIST uses a cylindrical steel transfer block (Eitzen and Breckenridge, 1987). Calibrations carried out on other materials would produce different transducer responses and, transducers calibrated on the steel block will respond differently when used on structures of materials other than steel (Eitzen and Breckenridge, 1987). Steel was initially chosen because it was expected that acoustic emission sensors would be used more with steel than on any other material.

The shape and the dimensions of the transfer block are such that it approximates an infinite half space, allowing Green's function methods to be used to predict the unloaded surface displacement. It is assumed that the loading effect due to the mechanical impedance of the transducer on the surface of the block has no effect on the displacement under the transducer.

2.4.3 The Nippon Steel Corporation method

If two transducers, both reciprocal in nature (Lampton and Burke, 1984) are coupled to a common medium with a known Green's function, the product of the source and receiver sensitivities can be found absolutely from the driving current in the source and the output voltage at the receiver. This technique is known as a reciprocity calibration and is common in a range of acoustic calibration applications. The method, as employed in AE by, for example, Hatano and Mori (1976) and Hatano et al (1998)), takes three reciprocal transducers and uses them in all the possible pairs of transmitting and receiving transducers. The input current and reception signal voltage for tone bursts of varying frequency are established for each pair together with the reciprocity parameter, allowing each transducer to be calibrated by measuring electrical signals only. To do this, the transducer characteristics are defined as the transmission voltage response in the transmitter configuration and the free-field voltage sensitivity in the receiver configuration. For the transmitter this is specifically defined as the vertical component of a Rayleigh-wave displacement velocity produced at a distance d from the transmitter for an input terminal voltage E_i. For the receiver it is specifically defined as the output open-circuit voltage produced by the arrival of a Rayleigh wave with a vertical component of displacement velocity u_R at the receiver's location.

The reciprocity parameter describes a transfer function of a Rayleigh-wave as it travels a distance 'd' from its origin to the location of the sensor. It takes into account the frequency of the Rayleigh wave and the material properties of the propagating medium. For a pair of transducers acting as a transmitting and receiving pair, the driving current in the transmitter and output voltage at the receiver form the electrical transfer impedance. This impedance divided by the reciprocity parameter gives the product of the sensitivities of the two transducers. In total, there are three of these similar equations, one for each possible pair of transmitter and receiver, from which the free field voltage sensitivity of each transducer can be found.

The NSC calibration facility uses a cylindrical steel transfer block similar to the NIST transfer block, measuring 1.1 m in diameter and 0.76 m long. The block is used to perform Rayleigh calibration (surface calibration) and longitudinal or P-wave calibration (through calibration) (Hatano et al., 1998). Again, the calibration is only valid when the sensor is used on steel structures, as calibrations performed on different mediums would produce different calibration results. A detailed overview of assumptions required for sensor characterisation is given by Hsu and Breckenridge (1981). The primary advantage of reciprocity as an AE sensor calibration technique is that it does not rely on a mechanical source.

2.4.4 Limitations of the methods

The absolute response calibration of an acoustic emission transducer although useful in the certification of a transducer's performance has inherent problems when trying to make an absolute or traceable measurement. There are essentially four reasons for this failure of absolute transducer calibration to provide absolute measurement.

The calibration described in section 2.4.2 is performed with reference to a non-contacting transducer, in this case a capacitance type. The reference transducer therefore exerts no resistive force on the surface; the transducer being calibrated however, does have a mass and is in contact with the surface. The surface motion is therefore altered by the presence of the transducer. The transducer is in effect calibrated for its response against a reference waveform that would exist in unloaded conditions, as if the transducer were not there. Thus any loading effect of the transducer under test is not included as part of the calibration. If the calibrated transducer is then used on a structure of the same material properties as the calibration test block the measured surface motion would be interpreted as the surface motion that would be observed if the transducer were not there. The calibration has therefore apparently overcome the loading effect of the transducer and allows for non-intrusive measurements of surface motion to be made. Unfortunately the loading effect is a function of the load impedance of the transducer and the source impedance imposed by the structure. Interaction between the source impedance and the load impedance determines the surface motion of the sensor face. The calibration is therefore only true on a structure or material that has identical mechanical impedance to the calibration test block. Since the effects of the source impedance and the load impedance are functions of frequency it is not easy to correct for this effect.

Secondly, the air gaps that are inevitably present between a transducer and the test surface pose a significant acoustic barrier at the frequencies used in acoustic emission. To improve sensitivity a coupling layer is almost always used to fill any air gaps present. Usually a liquid with a very low attenuation is used, but rigid couplants can be used if bonding of the transducer is necessary. Although it improves the sensitivity of the measurement several times, the couplant also introduces an unwanted variable into the measurement of acoustic emission. The thickness of the couplant layer can severely affect the measurement of surface motion and therefore leads to an uncertainty of measurement. Hill and El-Dardiry (1980) propose a theoretical solution for determining the transmission of longitudinal waves across couplant layers of different type and thickness. The procedure advised in the ASTM standard guide E750, is to use a consistent pressure in mounting the transducer to control the thickness of the couplant layer. Of course different coupling substances will lead to different interpretations of surface motion. If the calibration of the transducer is to be transferable, it is therefore necessary that the calibration be done using the same couplant with the same applied pressure that will be used in the measurement application.

Thirdly, when measuring surface motion on a non-simple structure, many wave modes are present and often interfere at the transducer face. The measurement of acoustic emission on a real system does not always allow the opportunity for discrimination between the wave modes. It is therefore difficult to determine the wave type to which the transducer is responding, and thus absolute interpretation of the measurement is unreliable. The majority of structures used in acoustic emission measurement systems are plate-like in nature and therefore Lamb waves are often the predominant wave mode measured. This is especially true for large structures where measurements are made at distances of a metre or so from the source. Lamb waves and Rayleigh waves by nature attenuate less over distance due to limited geometrical spreading. There is currently no standard method for the calibration of a transducer response to Lamb waves. This is mainly due to the difficulty in producing Lamb waves. Readers who are interested in the generation and detection of Rayleigh and Lamb waves and their use in flaw detection are referred to Viktorov (1967). Hill and Egle (1980) have considered the problem of single mode transducer calibration and have proposed a diffuse-field calibration technique for the transducer. The calibration procedure is based on the reciprocity method of calibration. The technique shows good correlation with face-to-face reciprocity and it attempts to address the calibration of the transducer in a way that is more representative of how it might be used to make measurements.

Finally, a further problem of calibration and indeed measurement, is the area of the transducer face that is in contact with the surface. For the most accurate calibrations, it would be preferable to be able to assume that there was no variation of amplitude or phase across the wave front impinging on the measurement area of the transducer. For compressional waves (through calibration) this can be approximated with distance from the source. For Rayleigh waves, shear waves and Lamb waves, however, this cannot be assumed or approximated, as a wave that has a displacement component normal to its direction of travel has a displacement (transverse wave) that is not only a function of time but also a function of position within the measurement area of the transducer. The output of the transducer is thus an average of the normal displacement. If a simplistic case is considered, where the wavelength of the wave and the transducer diameter are identical, then the output from a phase-sensitive transducer would be zero if the whole wavelength fell within the transducer's diameter. Although this is an over-simplification, it happens that many AE transducers have measurement diameters of the same order as the wavelengths present. This spatial-averaging or phase cancellation behaviour of measurement transducers is termed the aperture effect.

How the transducer responds has largely been ignored in this section. The assumption made thus far is that the transducer responds only to motion perpendicular to its face. Errors will therefore be made if the transducer is sensitive to tangential motion. Fortunately most acoustic emission transducers are relatively insensitive to tangential motion and the use of liquid coupling layers stops the transmission of shear forces. Ultimately the instantaneous displacement of a point at the surface is a three-dimensional vector but the output of the transducer is a scalar quantity.

The test block used for the transducer calibration should approximate a semi-infinite half space. This means that effects due to any boundaries may be ignored or gated out. Thus the measurement should detect only the arriving waveform with no interference from reflected waves. The frequency content of the measured waveform is a function of the source and sensor alone. A real test structure cannot be assumed to be a semi-infinite half space and reflections will be present and, ignoring attenuation, these will dominate at any natural resonances of the structure. If the same sensor were to be used to measure the response of two identical AE sources in different structures, the result would be two different responses, indicating that the medium plays a large role in the output from the transducer. Transducer calibration cannot therefore offer comparison between measurements made on different structures.

2.4.5 Improving reliability and repeatability

Other than transducer calibration, there are three ways in which calibration or verification techniques can be used to make acoustic emission measurement more repeatable and reliable. A major source of lack of repeatability and reproducibility is caused by coupling problems. Variations can be created by the use of different coupling mediums or the quality of the bond produced. Structures to which acoustic emission transducers are coupled or bonded are often of poor quality. Paint and heavy oxidisation can lead to major variation and even after careful surface preparation can lead to variations in measurement sensitivity of around 5% - 30%. If comparisons are to be made to measurements made on the structure periodically or at different locations then the ability to determine or correct for the change in sensitivity is essential.

It is possible to use a suitable source near to the sensor on each occasion that it is re-coupled to the structure. If this source is repeatable then the effect of coupling can be corrected for by the output of the transducer, given that all other re-couplings have been compared to the same source and the expected output for the source is known. For permanently bonded transducers this test can also be performed periodically to ensure no degradation of coupling with time This verification is currently performed mostly using the pencil lead break. It is very important for the source to be highly repeatable in nature as any variability in the source translates to an uncertainty in the coupling sensitivity correction.

Many acoustic emission applications use more than one transducer and can often utilise a whole array of sensors. With systems like this it is usually important that the sensors which comprise the measurement systems all perform in a known way, so that differences between sensors can be corrected for. The in-situ verification of the measurement system is also used to ensure that the measurements obtained are comparable to values obtained previously.

Many of the guides that exist for specific acoustic emission applications refer to the in-situ verification of the measurement system. These guides often consist of procedures that ensure the transducers in the measurement system provide at least the minimum required output for a pencil lead break performed at a given location. Many measurement system manufacturers provide self-calibration features built in to the measurement system. This usually entails each transducer in the system being pulsed with a voltage so that it is received by each of the other transducers in the system. This approach allows the measurement system to determine how each of the transducers or channels is performing and allows the measurement system to correct for this when measurements are made.

The effect of the medium on the measurement can be addressed using what is known as system calibration. When we refer to the system, we mean the structure, sensor and any other signal processing and acquisition equipment present. It can be defined as everything between the origin of the source and the actual AE signal measured. Whereas the transducer calibration alone does not offer the ability to transfer results between different measurement systems, system calibration can achieve this. It describes the methodology of referring the measured data to what would be measured from a quantifiable source, thus enabling the system to make traceable measurements and allowing measurements made on different systems to be compared to the same source. This type of system calibration can be termed absolute system calibration as the intention is to make an absolute assessment of the acoustic emission intensity traceable to standard units. All other considerations aside, the most important factor in system calibration is a quantifiable source traceable to standard units.

All the points discussed above rely on the use of a reference source. The transducer calibration is less reliant on this, in that the calibration is done with reference to a high fidelity transducer. However, the coupling verification, the measurement system verification and the system calibration techniques all require the use of a highly repeatable source. The system calibration relies further on a source that is quantifiable.

2.5 TRACEABILITY: WHAT DOES IT MEAN IN ACOUSTIC EMISSION?

2.5.1 Traceability and the National Measurement System

Measurement is a means of gaining more information about a physical value by applying a numerical value to it. The physical value being measured is termed the measurand. To make the measurement meaningful, the numerical value is stated with respect to fundamental or derived units. Underpinning all such physical measurements are national standards - a nation's ultimate reference standards, which realise in practical terms the internationally agreed definitions of the units of measurement (Clapham, 1992). National standards vary from a simple artefact such as the kilogram, to the realisation of the volt by means of the Josephson effect. As Clapham (1992) points out, there is a constant demand from industry and society for new standards. Whereas a century or so ago a limited number of basic measurements - mass, length, time, temperature, electric current - met most needs, now hundreds of standards are necessary. A detailed list of the range of measurement standards currently provided by NPL can be found on NPL's web-site at the following address:

http://www.npl.co.uk/npl/measurement/.

Primary measurement standards are maintained at NPL. A second tier of less accurate standards is maintained by laboratories and test houses throughout the UK. In many cases NPL's calibration facilities and those of the secondary laboratories are accredited by the United Kingdom Accreditation Service (UKAS), whose task is to ensure that equipment, staff and procedures meet the appropriate quality assurance standard ISO/IEC 17025 (1999), and that measurement standards are traceable.

The hierarchical structure outlined above also applies internationally with the aim of ensuring consistency of measurement. The definitions of all SI units of measurement are agreed internationally and an extensive programme of research exists to realise these standards with greater accuracy. Regular comparisons ensure that the national standards which realise the SI definitions are consistent.

Calibration is needed to ensure the measurement made of a measurand by a measurement instrument represents that of the defined standard. Generally this is performed by comparing the output from the instrument being calibrated against the output from a standard instrument of known accuracy, when the same input is applied to both instruments. The input would also be known and in many cases would be a standard reference source or calibrator designed to test the instrument across its whole input range. The calibration works in a chainlike structure where every instrument in the chain is calibrated against a more accurate instrument immediately above it in the chain. To make the chain traceable from the measurement itself to international standards, the chain must be unbroken and uncertainties stated at each stage. This complete chain is known as traceability (Ehrlich and Rasberry, 1998).

2.5.2 Traceability in acoustic emission: the current position

Acoustic emission currently has no centre of excellence in the UK, and at present transducer calibrations are only carried out by the National Institute for Science and Technology (NIST), USA and the Nippon Steel Corporation (NSC), Japan, as was explained earlier in this report. Of course equipment suppliers such as AE transducer manufacturers provide calibrations, but these may not always be traceable to national standards and are often relative in nature. As we have seen, there are codes that exist in AE that cover all aspects of quality assurance to in-situ verification of measurement systems. The work reported here aims to improve on methods of transducer calibration by developing methodologies that will allow calibrations to be made traceable to base SI units and thus national standards.

2.5.3 Good practice requires traceability

The demand for traceable calibrations will depend on the requirements of users of acoustic emission transducers. Here, it is instructive to review the measurement advice on good measurement practice provided by the DTI-funded National Measurement Partnership (NMP). For more information about the NMP, refer to its web-site at:

http://www.nmpuk .co.uk/advice/good_measurement_practice.html.

The NMP sets out a set of guiding principles for good measurement practice:

1. Measurements should only be made to satisfy agreed and well-specified requirements.
2. Measurements should be made using equipment and methods which have been demonstrated to be fit for purpose.
3. Measurement staff should be competent, properly qualified and well informed.
4. There should be both internal and independent assessment of technical performance of all measurement facilities and procedures.
5. Measurements made in one location should be consistent with those made elsewhere.
6. Well defined procedures consistent with national or international standards should be in place for all measurements.

In support of the fifth point above, the guidance note argues that to demonstrate consistency all equipment should be properly calibrated to national standards, ideally using accredited calibration laboratories. Self-assessment is also essential. Regular checks should be made on the quality of measurements using control samples with known parameters.

2.6 THE NPL APPROACH

Chapter 3 sets out in detail the experimental approach we have adopted to providing traceable calibrations of acoustic emission transducers. However, prior to a specific discussion of acoustic emission, it is helpful to review NPL's experience and expertise in providing primary standard acoustic calibrations, especially in the application of optical techniques to the measurement of acoustic particle displacement and velocity.

NPL has unique acoustic facilities and can provide a large number of acoustic measurements and calibrations. Some of the basic acoustical calibration services include:

- Pressure calibration of laboratory standard microphones, 31.5 Hz to 20 kHz;
- Free-field calibration of microphones, 31.5 kHz to 12.5 kHz;
- Free-field calibration of ultrasonic hydrophones above 1 MHz;
- Hydrophone calibration by laser interferometry, 1 MHz to 60 MHz;
- Free-field calibration of underwater acoustic transducers by the reciprocity method, 1 kHz to 500 kHz.

These services, and UKAS-accredited calibration laboratories, are underpinned by primary standards of measurement for sound in air and water that are maintained at NPL.

For sound in air, the primary standard ‘acoustic pascal’ is realised through a determination of the sensitivity of a laboratory standard microphone using the so-called reciprocity method. For frequencies between 1 Hz and 250 Hz, a laser pistonphone has also been developed in which the sound pressure is calculable (Barham, 1994). For sound in water, and in the frequency range above 0.5 MHz, the primary standard for the calibration of hydrophones is a laser interferometer measuring acoustic particle displacement, from which the acoustic pressure is derived. In the frequency range 1 kHz to 500 kHz, the primary method of calibrating hydrophones is three-transducer spherical-wave reciprocity.

Optical techniques already provide primary standards at NPL. Primary free-field calibration of hydrophones in the megahertz frequency range up to 60 MHz is realised using optical interferometry (Bacon, 1988; Esward and Robinson, 1999). In this method, a thin plastic membrane (pellicle) is placed in the field of a transducer and a specially-designed Michelson interferometer is used to measure the acoustic particle displacement in the field. The pellicle is optically reflecting but acoustically transparent so that it follows the motion of the wave, and the acoustic pressure in the field is calculated from the measured displacement. The hydrophone is then substituted for the pellicle and calibrated by measuring the output voltage corresponding to the known acoustic pressure. Advantages of this method are its direct traceability to primary standards of length and its insensitivity to the properties of the transducer.

In another application, a pellicle is also used as the target for the long-path velocity interferometer developed at NPL for measuring and characterising acoustic shock waves from lithotripters (Galloway et al, 1995). The laser beam incident on the pellicle is Doppler shifted depending on the velocity of the pellicle in the acoustic field and this Doppler-shifted beam is then compared with the reference beam that has been phase delayed using a glass block. This process makes the output sensitive to the pellicle velocity, and velocities up to 100 m s^{-1} can be measured with a bandwidth of 100 MHz. Of note here is that the optical head is immersible in water and the laser beam delivery is through optical fibres.

History shows that many primary standard facilities are based on simple scientific/physical principles even though they may involve relatively complex implementations. Furthermore, perhaps the most important aspect of a primary standard is having a full and total understanding of how it works and all the elements of which it is comprised. From this knowledge it is possible to analyse the performance of the equipment. For instance, often it is necessary to model theoretically the standard, or aspects of its performance, in order to build up the metrology base and detailed error budgets. One area of acoustical theory in which

NPL has substantial experience is the modelling of acoustic propagation problems, including the application of finite element methods to such problems.

Finally, NPL has taken an active part in the development of specification standards through the International Electrotechnical Commission. As an active member of Technical Committee 29, Electroacoustics, NPL contributes to IEC 61094 (Part 2) that specifies the reciprocity method for the laboratory standard microphone calibration, the basis for primary standards held worldwide, as well as contributing to other standards on acoustical instrumentation and methods. NPL is also closely involved with IEC Technical Committee 87, Ultrasonics, a committee that develops specification standards for the calibration of hydrophones and the measurement and characterisation of ultrasonic and underwater acoustic fields.

The experience outlined above leads us to conclude, together with our partners in this project, that laser interferometry techniques offer the most direct route to the measurement of the surface displacements arising from acoustic emission signals. The combination of optical methods with well-characterised, repeatable source transducers of small size, and an optical quality glass test block, provides a solid foundation on which to build a high-quality calibration facility for acoustic emission transducers. The next chapter of this report sets out in detail the experimental approach.

3 ESTABLISHING ACOUSTIC EMISSION CALIBRATION AT NPL

This chapter sets out the calibration methodology which has been adopted and details the specifications of the main components of the measurement system. The results of the experimental evaluation of the method, including initial calibrations of some typical acoustic emission transducers are then presented in chapter four of this report.

3.1 OVERVIEW OF THE PROPOSED METHOD

Our preferred approach is to use a laser interferometer as the detector of the surface displacement of the test block. The use of such techniques can be traced back approximately 25 years to research initially carried out in the USA. Scruby and Drain (1990, pp 200-207, pp 384-394) give a useful overview of the application of lasers in acoustic emission work. As they point out, the laser offers non-contact measurements with both high bandwidth and high spatial resolution. Early work with lasers concentrated on their use as sensors of acoustic emission events in engineering materials rather than on their use as a mean of calibrating acoustic emission transducers. However there soon developed an interest in using lasers as a means of characterising the response of acoustic emission transducers, including capacitative transducers of the type described in chapter two (Scruby and Drain, 1990, pp 388-391). Scruby has documented his own work in the use of lasers to study the response of point-contact piezoelectric transducers in a report prepared for the UK Atomic Energy Authority (1984).

In the early 1980s work had also been carried out at Siemens to evaluate acoustic emission transducers. This research, as reported by Niewisch and Krämmer (1982), used an interferometer designed by Photometric Consultants Ltd, the suppliers of the interferometer commissioned for the current project, to measure the surface displacement of a test block when a glass capillary was broken. In the 1990s two American researchers, Jacobs and Woolsey (1993) reported the use of a broadband laser interferometer to develop a transfer function for a piezoelectric acoustic emission transducer. Their aim was to convert the relative transducer output to an absolute measurement of surface velocity, taking into account the transducer's frequency response. Their approach can be regarded as a precursor of the current work. Rogers (2001) documented the response of a Photometric Consultants Ltd laser interferometer to a pencil lead-break simulated acoustic emission source. Further details of the Photometric Consultants interferometer are set out in section 3.3.

Our preferred calibration method is to use a point contact piezoelectric transducer as a repeatable source which can be used in both broadband and narrowband mode. The transducer is coupled to one side of a glass block. The longitudinal waves generated by the transducer are measured at the opposite side of the block, firstly by the interferometer and then by the acoustic emission transducer to be calibrated. Comparison of the two received waveforms allows the sensitivity of the AE transducer to be derived as a function of frequency. An advantage of using the glass block is that the laser beam can also be directed through the block from the same side as the source transducer so that the movement of the block surface can be detected with the AE transducer in place, thus allowing the effect of surface loading by the AE transducer to be investigated. A schematic diagram of the proposed experimental set-up is shown in figure 1a and a photograph of the actual set-up is shown in figure 1b.

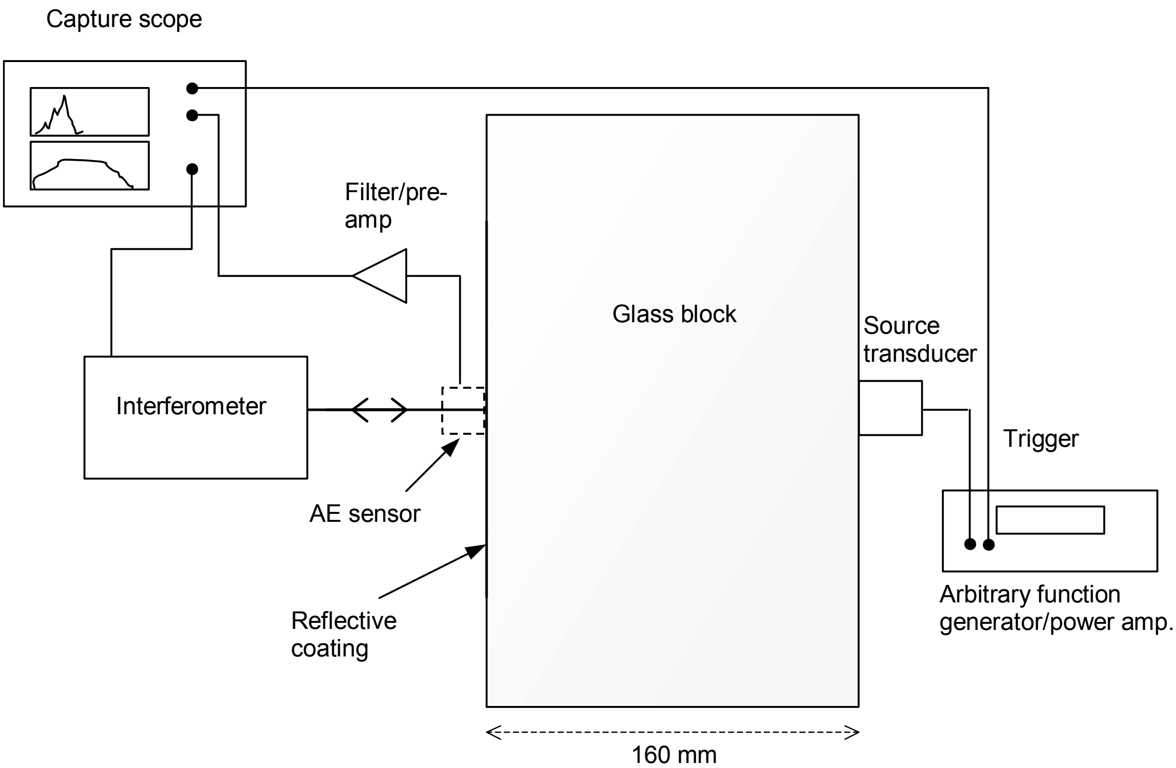

Figure 1a: Lay-out of through-transmission calibration system

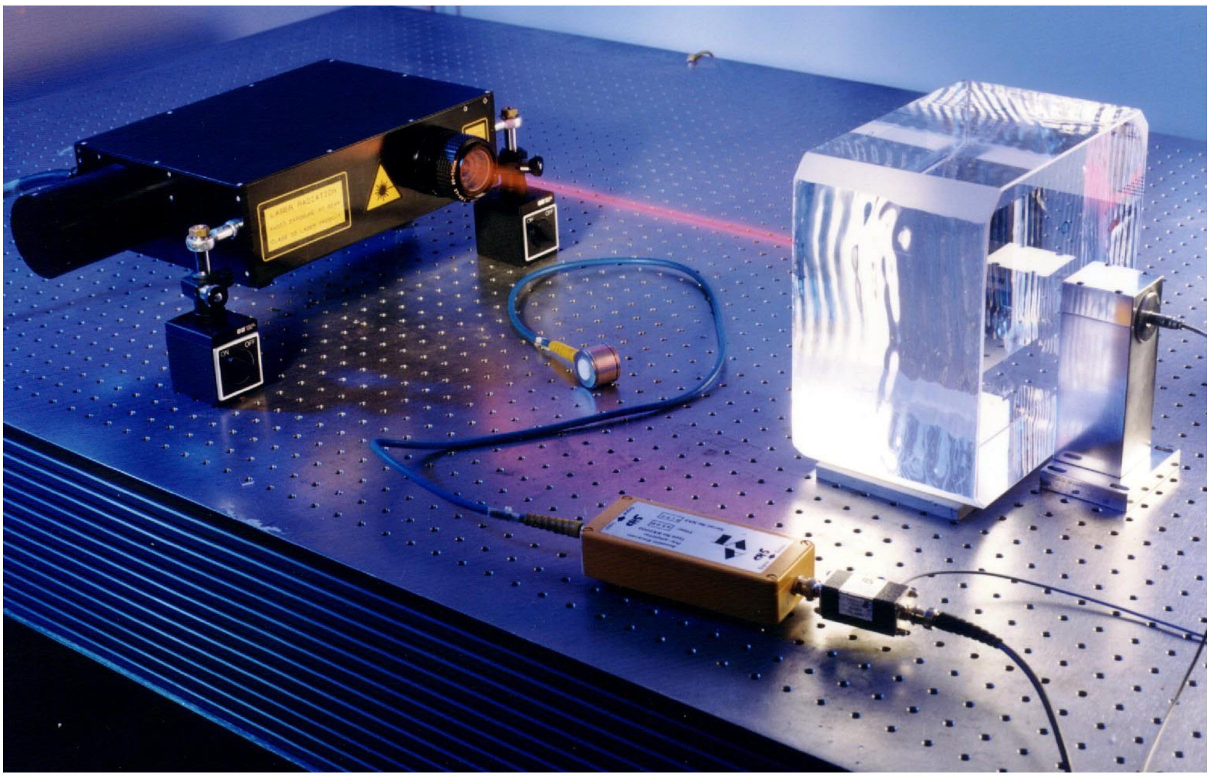

Figure 1b: Experimental set-up as shown in figure 1a

3.2 PREFERRED WAVE MODES

As the reader will have realised from the above section, the intention is to detect and measure surface displacements arising from compressional waves arriving normal to that surface. In any realistic engineering structure in which acoustic emission signals are propagating, there is the possibility that a number of wave modes will exist simultaneously and not all of these will generate normal surface displacements. For example, a plane shear wave normally incident on the surface will not generate normal displacements, nor will obliquely-incident shear waves whose plane of polarisation is perpendicular to the plane of incidence (Scruby and Drain, 1990, p208). Displacements normal to the surface of interest are often referred to as out-of-plane components, whereas transverse displacements which travel parallel to the surface are labelled as in-plane displacements. Some wave modes, such as Rayleigh surface waves, contain both in-plane and out-of-plane components. For a full discussion of Rayleigh waves, and Lamb or plate waves, including their propagation modes, and methods of generating and detecting them the reader is referred to Viktorov (1967).

It is difficult to envisage how one might make optical measurements of the in-plane displacement of a well-polished surface. However, if there is some surface roughness present it is possible to make measurements with a laser beam at oblique incidence. The use of two interferometer beams at oblique angles would allow the in-plane and out-of-plane displacements to be deduced. The reflecting surface could also be treated to make it behave as a diffraction grating. Scruby and Drain (1990, pp 210-21) review the possible techniques. Drain himself (1980) has proposed the use of a differential laser Doppler technique to measure in-plane displacements.

For the purposes of repeatable calibration, it is essential that only one wave mode is present and that this mode should be easily detectable both by the transducer under test and by the interferometer. In addition, it is necessary to consider the effect of the detector size on the measurement. Although, for practical purposes, it is possible to regard the laser interferometer beam as a point receiver for the acoustic wavelengths of interest, this is not the case for any acoustic emission transducer which is likely to be calibrated. At 1 MHz the wavelength of compressional waves in glass is 6 mm, whereas the laser spot size is approximately 0.1 mm in diameter. However, it is likely that any AE transducer submitted for calibration will be at least 6 mm or more in diameter. It is therefore essential that a calibration geometry and wave mode are chosen to minimise spatial averaging and phase cancellation effects. The detection of compressional waves generated by a source of small size and transmitted through a thick block is likely to limit such effects, thus reducing the need to correct the AE transducer measurements for spatial averaging effects. This geometry also removes the need to consider the directional response of the AE transducer, as one is detecting wave fronts which can be regarded as both planar and normally incident on the transducer. Further consideration of this issue can be found below in section 3.4 of this chapter, where the question of test block dimensions is reviewed.

Future work will consider the question of calibrating a transducer for its response to surface waves and to shear waves. However, for the purposes of the current study, investigations and calibrations are confined to compressional waves normally incident on the transducer face.

3.3 THE INTERFEROMETER: DESIGN AND SPECIFICATION

The laser interferometer to be provided as one of the main deliverables of this project has been designed and built by Photometric Consultants Ltd, who specialise in building interferometers for a wide range of vibration measurement problems. The use of a Photometric Consultants' interferometer by Siemens for detecting acoustic emission signals has already been mentioned (Niewisch and Krämmer, 1982). Other applications in which the company's devices have been used include the investigation of the vibration of cooling towers, dams and buildings (Winney, 1978, Corti et al, 1982, Ellis, 1998, Bougard and Ellis, 1998).

The basic interferometer specification was that it should have a bandwidth of 20 kHz to 3 MHz. The noise equivalent displacement should be a maximum of 10 pm rms with a target maximum of 5 pm rms in the absence of intermode beats, measured on a high quality target mirror with reflectance greater than 90%. The range to the target was to be 400 mm from the output lens and a focusing adjustment was to be provided to maximise the signal return. The interferometer should incorporate automatic calibration and calibration checking systems. Laser power was to be 5 mW or less, thus putting the device in the newly-defined class 3R (see amendment 2 to the International Standard IEC 60825-1).

The interferometer uses a 633 nm wavelength helium neon laser as a light source. The operation of the interferometer is straightforward. The light reflected from a vibrating object is mixed with a reference beam on a photodetector. The path length difference between the target and reference beam is held constant by a servo-driven path length compensator, giving phase quadrature between the beams. The system acts as a phase or path length discriminator with the photodetector current being proportional to the displacement of the target, for frequencies higher than the response speed of the compensator, provided that the displacements are small and there is a constant returned light level.

As the returned light level can vary, an automatic calibration technique is used to maintain constant output sensitivity. This is done by injecting a phase modulation equivalent to a target displacement of 40 nm at 14.74 MHz. An automatic gain controlled amplifier maintains a constant level of the 14.74 MHz signal at the output. A low pass filter is then used to eliminate this calibrator signal from the output. The second harmonic of the calibrator signal, 29.48 MHz, is phase detected against a 29.48 MHz reference to provide a control signal for the path length compensator system.

Two test functions are provided to allow the system calibration to be checked. The first allows the injection of a cyclic displacement of the compensator to display quarter wave output signals representing 158 nm peak to peak displacement. The second applies a test signal of 25 kHz to the modulator crystal, giving a signal equivalent to 2.5 nm peak-to-peak of target displacement.

Figure 2 shows a schematic diagram of the interferometer's basic components.

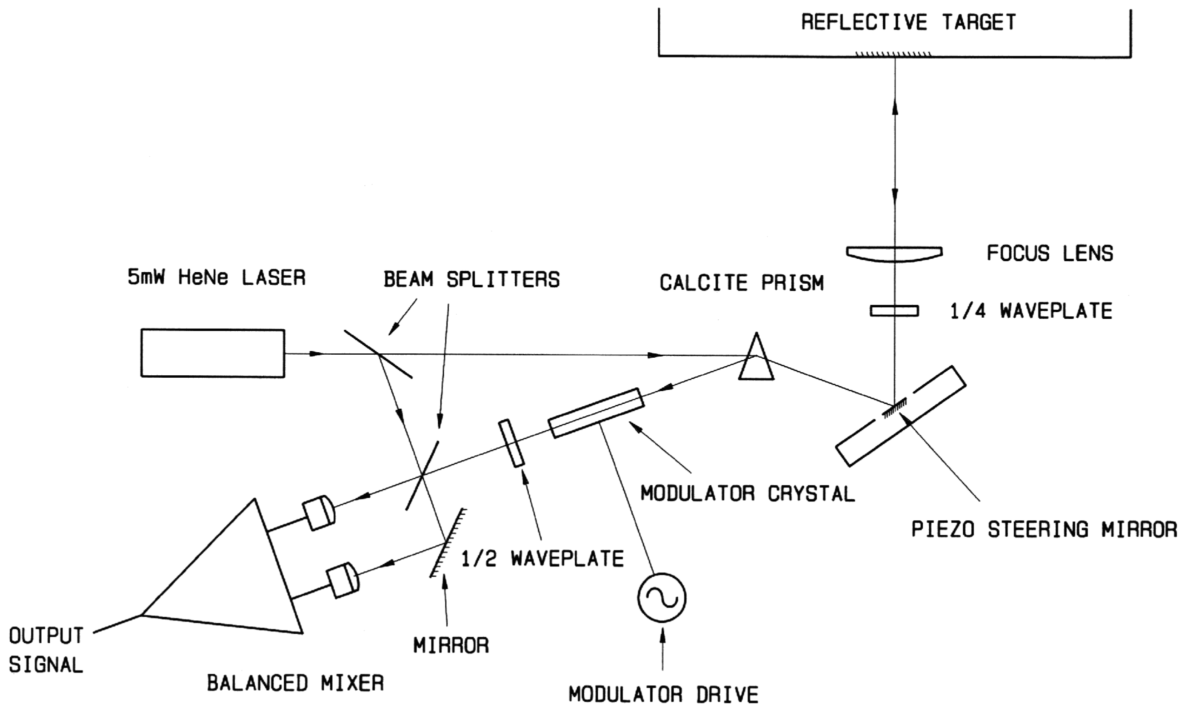

Figure 2: Basic components of laser interferometer system

As stated earlier, it was not possible to use this interferometer for the majority of measurements reported. However, some initial results with the PCL interferometer are given in section 4.6.

3.4 CHOICE OF TEST BLOCKS

Although it might seem preferable to employ metals as test block materials for acoustic emission and one of the current authors has extensive experience of working with cylindrical aluminium test blocks (Theobald, 2002) it was decided that glass would be used as the test block material. The reasons for this choice were:

1. It is easy to polish and coat glass materials to provide a suitable surface for the optimum reflection of the laser signal.
2. It is difficult to produce large samples of metals, and of aluminium in particular, which have homogeneous acoustic properties.
3. An optically transparent material allows the laser interferometer beam to be directed through the block at any surface of interest.
4. The sound speed of longitudinal waves in glass lies in the range from 5200 ms^{-1} to 5700 ms^{-1} and the shear wave speed in the range 3000 ms^{-1} to 3500 ms^{-1}. These values are comparable to aluminium which has a longitudinal wave speed of 6400 ms^{-1} and a shear wave speed of 3100 ms^{-1}.

A block of Schott NBK7 standard optical quality borosilicate glass of approximate dimensions 240 mm by 250 mm by 160 mm was purchased. Final polishing and the coating of an area of the working surface with a soft aluminium coating were carried out in the optical workshop at NPL. Figure 3 shows a photograph of the block after polishing and coating. As was mentioned earlier, at a sound speed of 6000 ms^{-1} the wavelength of a 1 MHz frequency sound wave is 6 mm and that of a 100 kHz wave 60 mm. The time of flight for a compressional wave through a 160 mm thick glass block is approximately 27 microseconds. If the source transducer and the laser spot are located opposite each other on either side of the 160 mm thickness dimension of the block in the centre of their respective faces, then the first reflection from the side walls of the block will traverse a path approximately 130 mm longer than the direct path from the source transducer to the laser. The main limitation on the low frequency limit of the calibration would therefore appear to be the response of the acoustic emission transducer to be calibrated. For broadband receivers time gating techniques should be satisfactory for the rejection of echoes and reflections at frequencies down to 100 kHz. However, the resonant behaviour of narrowband transducers will make it difficult to separate the response to the direct wave from the effects of the later reflection and echo arrivals at such low frequencies, and this is likely to be true for both pulsed and tone burst source signals. Achieving accurate calibrations with low measurement uncertainties in such cases may eventually require the use of relatively sophisticated signal processing techniques including the prediction of steady state transducer responses from measurements in reverberant conditions, an area in which NPL already has experience (Robinson and Harris, 1999).

To establish the acoustic homogeneity of the glass block a systematic investigation of the variation of the speed of sound as a function of position was carried out. The results of this study are set out in chapter 4 of this report.

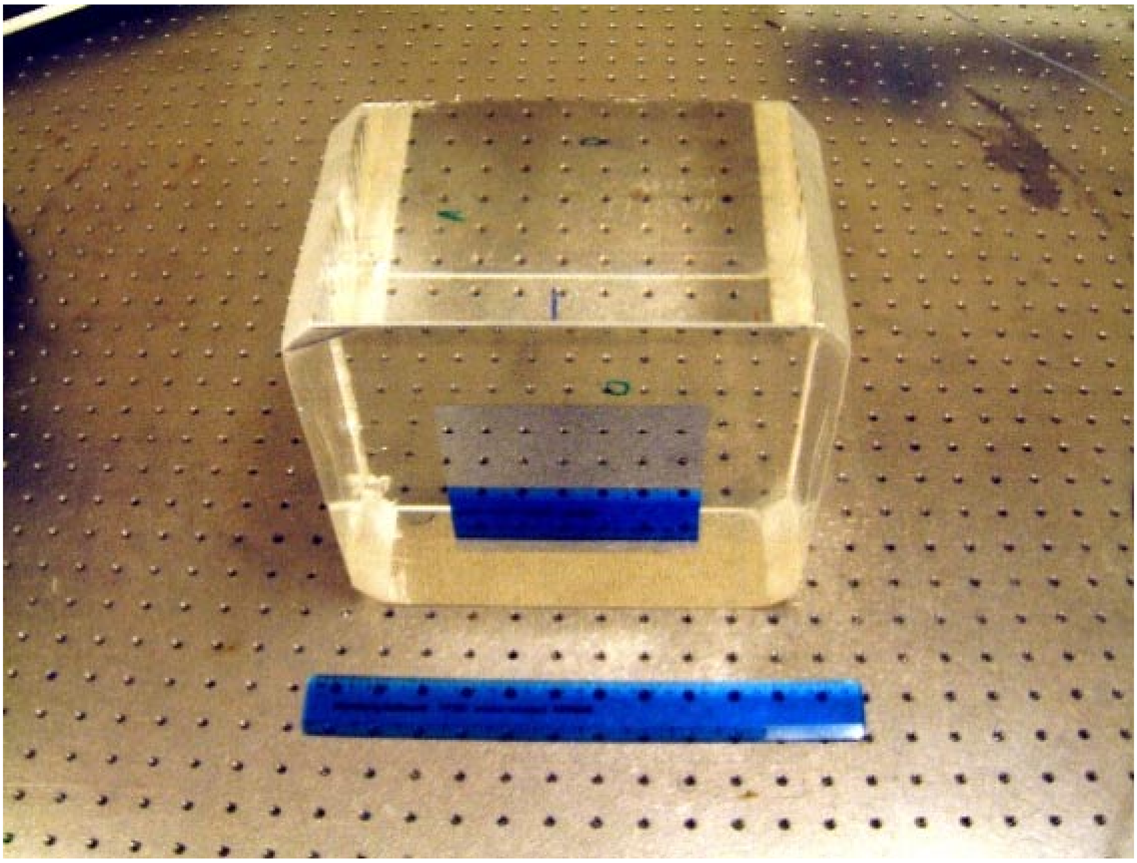

Figure 3: Glass block after polishing and the application of an aluminium coating

3.5 SOURCE TRANSDUCERS

The primary requirements for the source transducer to be employed in the calibration system described here are repeatability and ease of coupling. In addition, the source should possess a broad bandwidth and be of sufficiently small diameter that measurements always take place in its far field. Various experimenters have reported successful use of a range of designs of point contact transducers, including transducers with conical elements (Niewisch and Krämmer, 1982; Scruby, 1984; Proctor, 1982; Greenspan, 1987; Evans, 1997).

The NIST acoustic emission calibration system is based on the use of point contact, conical transducers (Proctor, 1982; Greenspan, 1987), in which a conical PZT element, 2.5 mm in thickness and with a 1.5 mm diameter contact is attached to an extended cylindrical brass backing. In our view, this type of design has advantages as a source transducer. As Evans (1997) point outs, the small contact area of such designs reduces aperture effects and coupling variability, and although a conical element has more mechanical resonances than a disc-shaped element, these resonances are less dominant, giving such transducers an improved broad band response. As receiving transducers they are less sensitive than conventional acoustic emission transducers.

As Evans had manufactured a range of conical transducers with both brass and tungsten-epoxy backings for his own Ph D research, we sourced additional conical transducers suitable for use in the calibration system from him. The specification was based on the tungsten-epoxy backed version. Figure 4 shows a schematic of this design. The purpose of the brass shim is to act both as an electrical contact and as a wear plate.

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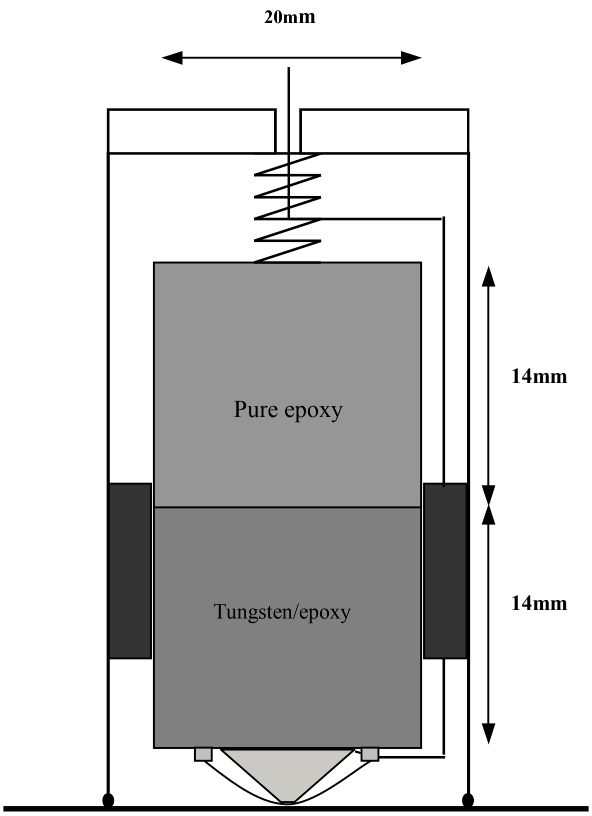

Figure 4. Tungsten epoxy backed conical piezoelectric transducer

The key features of the specification were as follows:

1. the piezoelectric element to be machined using a diamond tip to a thickness of 3 mm, a base diameter of 10 mm, and a 1 mm tip diameter;
2. the piezoelectric element to be bonded to the backing using silver-loaded epoxy;
3. the backing consists of 14 mm of tungsten loaded epoxy and 14 mm of pure epoxy, with total dimensions 20 mm diameter x 28 mm height;
4. the case to be of aluminium;
5. PTFE guides to be used to maintain the orientation of the backing within the case;
6. the backing and element to be spring loaded to maintain a 10 N force on the test block;
7. a 50 micron thick brass contact shim to be provided, but without bonding to the piezoelectric element.

Figure 5 is a photograph of a conical transducer manufactured previously by Dr Mark Evans for Brunel University. A 50 p coin provides a size reference in this image. The brass shim is clearly visible across the tip of the conical element. Again, it was not possible to use this for the majority of measurements.

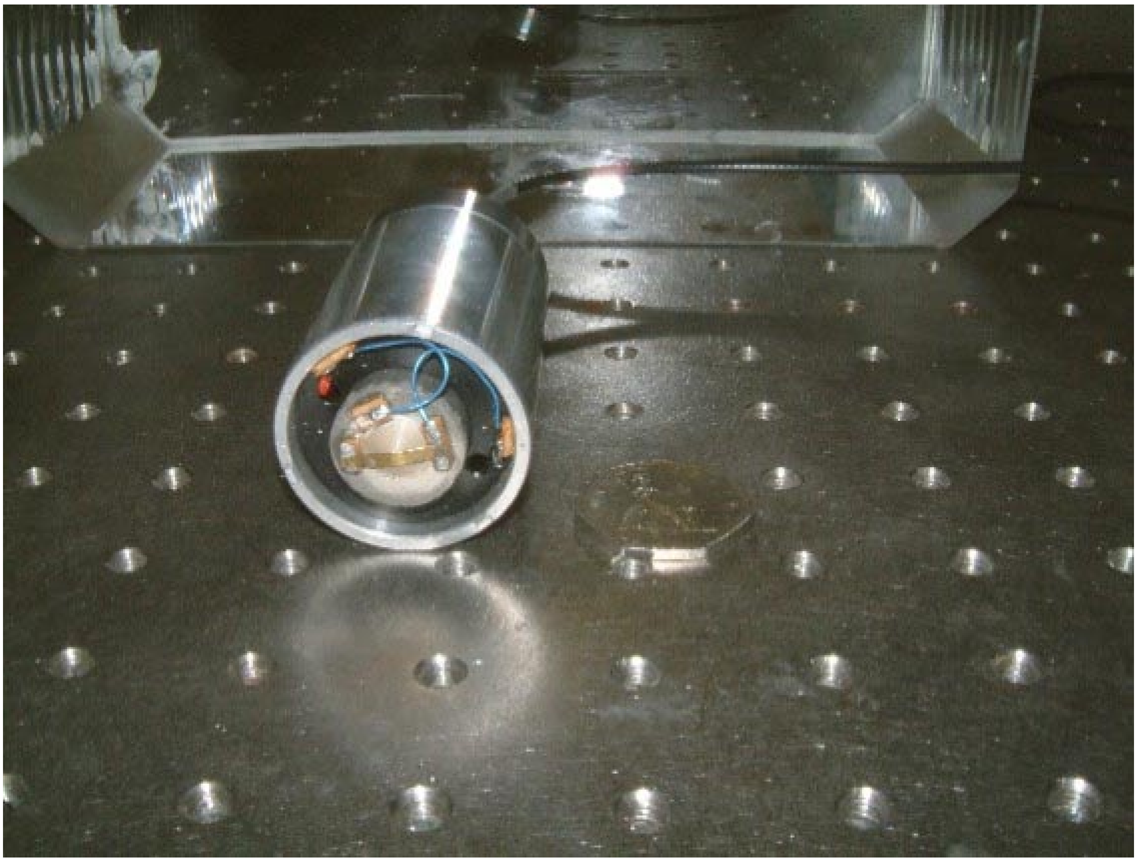

Figure 5: Conical piezoelectric transducer to be used as acoustic source for calibration

3.6 COUPLING TRANSDUCERS TO THE TEST BLOCK

The question of the variability of coupling to the test block is important both for the conical source transducer and the acoustic emission transducers under test. In addition, once the source transducer is in place on the test block, there is no need to move it during measurements or from one set of measurements to the next. This is not true for the AE transducers under test. Indeed, establishing the effect of variations in coupling is a vital part of acoustic emission transducer characterisation. Such variations will contribute to the calibration measurement uncertainties, and are likely to consist of both systematic and random effects, which may also vary with the size of the transducer undergoing calibration. Some results of preliminary investigations of coupling variability are included in the next chapter.

Further development work may also required on the conical transducer to reduce possible coupling problems. For example, the brass shim could be replaced with a polyurethane tip, and this would have the advantage of reducing any coupling variability due to the shim itself. The electrical contact could be taken along the side of the conical element in this configuration. Damage to the polyurethane tip could be avoided if the transducer were to be designed such that it could be placed on the surface before the sensing element is lowered and locked into position. Use of a polyurethane tip may also have advantages in laboratory conditions, as the current glass test block surface is of good quality and movement of the transducer would be limited once in place.

4 EVALUATING THE PROPOSED METHOD: RESULTS

4.1 INTRODUCTION

In this chapter the main results from a systematic evaluation of the proposed method are set out. The chapter begins with an account of an investigation of the acoustic properties of the test block. This is followed by examples of calibration results for some typical acoustic emission sensors. To allow us to meet the time deadlines for the completion of the project, these calibrations were carried out with an alternative interferometer which was already available at NPL, rather than the Photometric Consultants' interferometer, and with the Panametrics non-destructive testing transducer described in the next section. The disadvantage in using the alternative interferometer, which was designed for wide bandwidth ultrasonic hydrophone calibration, was that its noise equivalent displacement was a factor of between 8 to 10 times worse than that of the Photometric Consultants' interferometer over the bandwidth of interest.

Some aspects of the calibration methodology were then examined in more detail, including signal processing and data windowing questions, and the variability introduced by coupling and re-coupling the sensor during a set of repeat calibrations. Finally, some of the key results from the evaluation of the performance of the Photometric Consultants' interferometer and of conical transducers are presented.

4.2 INVESTIGATING THE ACOUSTIC PROPERTIES OF THE TEST BLOCK

4.2.1 Sound speed

A systematic investigation of the acoustic properties of the glass test block was carried out. The speed of longitudinal waves through the block was measured as a function of position, to identify the extent of any spatial variations of speeds throughout the volume of the block material.

A series of pulse-echo tests was carried out using a 0.5 MHz 29 mm diameter Panametrics NDT transducer. Measurements were made at a set of 63 locations on the 163 mm by 256 mm block surface. The locations were chosen on a rectangular 7 by 9 grid centred on this surface with a grid spacing of 17.5 mm in each direction. A digital oscilloscope was used to record the first and second reflections from the block face opposite the transducer. The time sampling interval employed was 10 ns and the time of flight of the pulse was determined by taking the time difference between the peak amplitude of the first and second reflections. The thickness of the block in the direction of wave propagation is 242.2 ± 0.5 mm. No systematic variation of sound speed with position was observed. The temperature of one surface of the block was measured regularly with a thermocouple during the course of the experiment, which lasted approximately 7 hours. The maximum and minimum measured surface temperatures were 26.2°C and 21.5°C and there appeared to be no correlation between sound speed and temperature. The block had been left to equilibrate in the laboratory for 24 hours before the measurements were carried out. It is likely that the thermocouple measurement does not reflect the internal temperature of the block.

The mean measured compressional wave speed was 6014.3 ± 4.2 m/s, where the uncertainty is the standard deviation of the measured data. Taking into account the uncertainty in block thickness, the best estimate of the speed of longitudinal waves in the block is 6014 ± 17 m/s at the 95% confidence level. This represents a wavelength of 12.028 ± 0.074 mm at 500 kHz. At a frequency of 500 kHz and a sound speed of 6014 m/s, one degree of phase variation in glass represents a path length difference of 0.0334 mm. Thus the measured variation in sound speed translates to a phase variation of more than 2 degrees of phase. For shorter wavelengths the phase error is greater and would be more than 4 degrees of phase at 1 MHz.

4.2.2 The size of the glass block

Many acoustic emission sensors are highly resonant devices. Their response to an impulse is to "ring" for some time. This poses problems for calibration carried out using test blocks of finite size. The difficultly can be demonstrated by examining a pair of interferometer and acoustic emission sensor waveforms as they respond to the same input signal. A damped Panametrics 500 kHz NDT transducer was coupled to one side of the glass block so that compressional waves could be transmitted through the block in the 163 mm thickness direction. The transducer was driven with a single cycle of a 500 kHz sine wave. The interferometer was used to sense the displacement of the block surface opposite the transducer. The drive signal to the Panametrics transducer was used to trigger the interferometer. The signal detected by the interferometer is shown in figure 6, where the trigger point for this trace is at 29 µs. The trace shows a number of important features. The direct signal from the transducer arrives at the surface approximately 27 µs after the trigger and lasts approximately 6 µs. At approximately 38 µs after the trigger there are indications of waves which have reached the detection point by an indirect route, perhaps representing signals from echoes within the source transducer, which then appear to be followed by signals representing reflections from side walls of the block. Finally, 54 µs after the direct signal the first back wall echo is seen. Note also that waves which are not normally incident on the surface at the interferometer's detection point will be underestimated in amplitude as the interferometer detects only motion normal to the measurement surface. In addition, any shear waves with their place of polarisation parallel to the surface will not generate any out-of-plane motion, and so will remain undetected. Figure 7 shows that the AE sensor's resonant response prolongs the time duration of the direct and first echo signals and that the sensor also clearly detects signals arriving after the direct signal but before the first back-wall reflection. These are reflections from the side wall, including both longitudinal and shear wave components and appear more clearly in the sensor trace than in the interferometer trace.

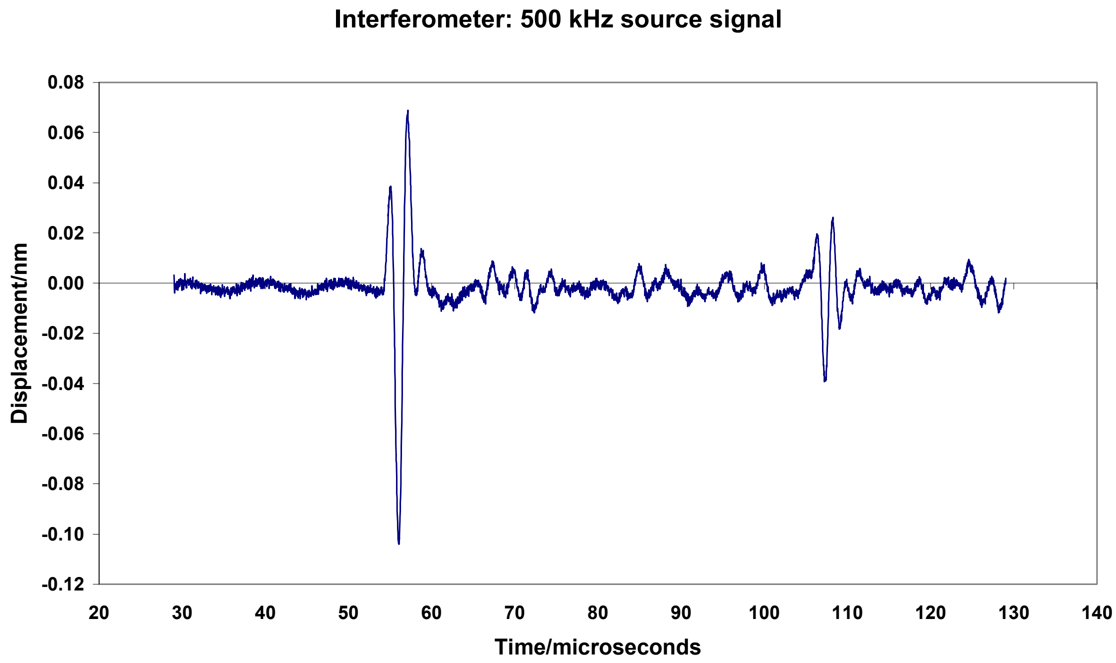

Figure 6: interferometer, response to 500 kHz single cycle pulse

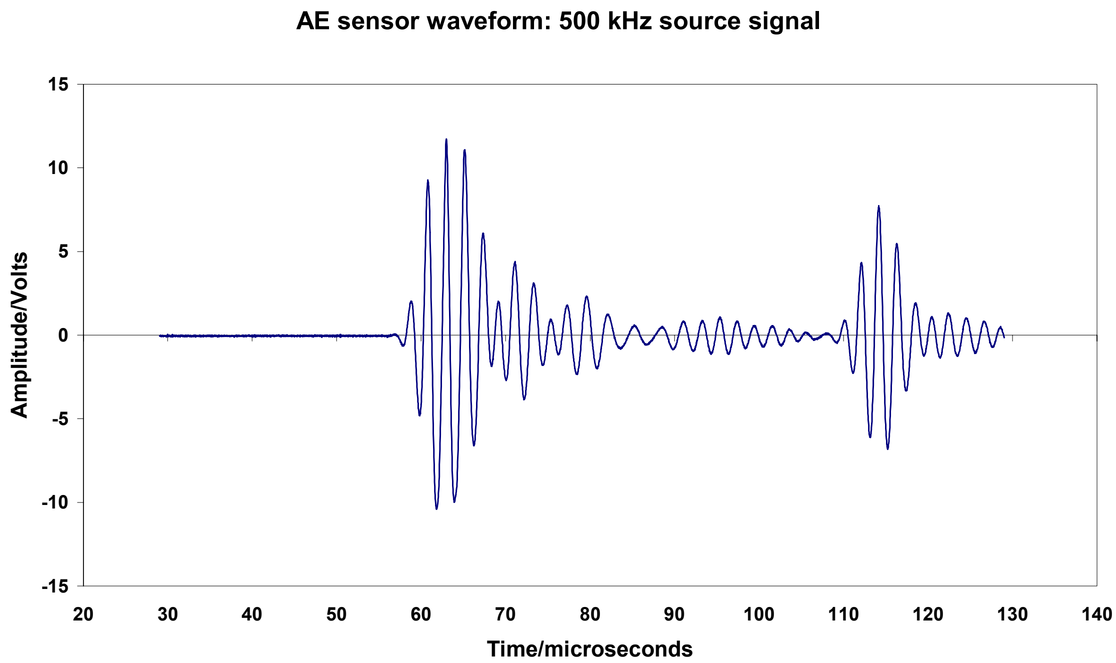

Figure 7: AE sensor, response to 500 kHz single cycle pulse

4.3 CALIBRATING AE SENSORS: RESULTS

Calibration of two AE sensors provided by Lloyd's Register was performed using the NPL laser interferometer and the glass test block. The source transducer was an untuned heavily-damped broad band Panametrics 1.5 inch diameter 0.5 MHz V389-SU immersion transducer which was coupled to the glass test block with a water-soluble medical ultrasound coupling gel. It was driven directly with a 0.5 V peak-to-peak 25 cycle tone burst from an Agilent function generator.

The AE sensors were:

A. An AVT NS-2004-0225 type with a nominal frequency of 450 kHz connected to a 40 dB gain pre-amplifier and filter unit with a 490 kHz centre frequency and a bandwidth of one octave either side of the centre frequency. The diameter of the active element was 18 mm.
B. An NS-3301 150 kHz nominal frequency sensor connected to a PA3301 40 dB gain pre-amplifier and filter. The active element diameter was also 18 mm.

Figure 8 shows a photograph of sensor A reflected in the glass test block.

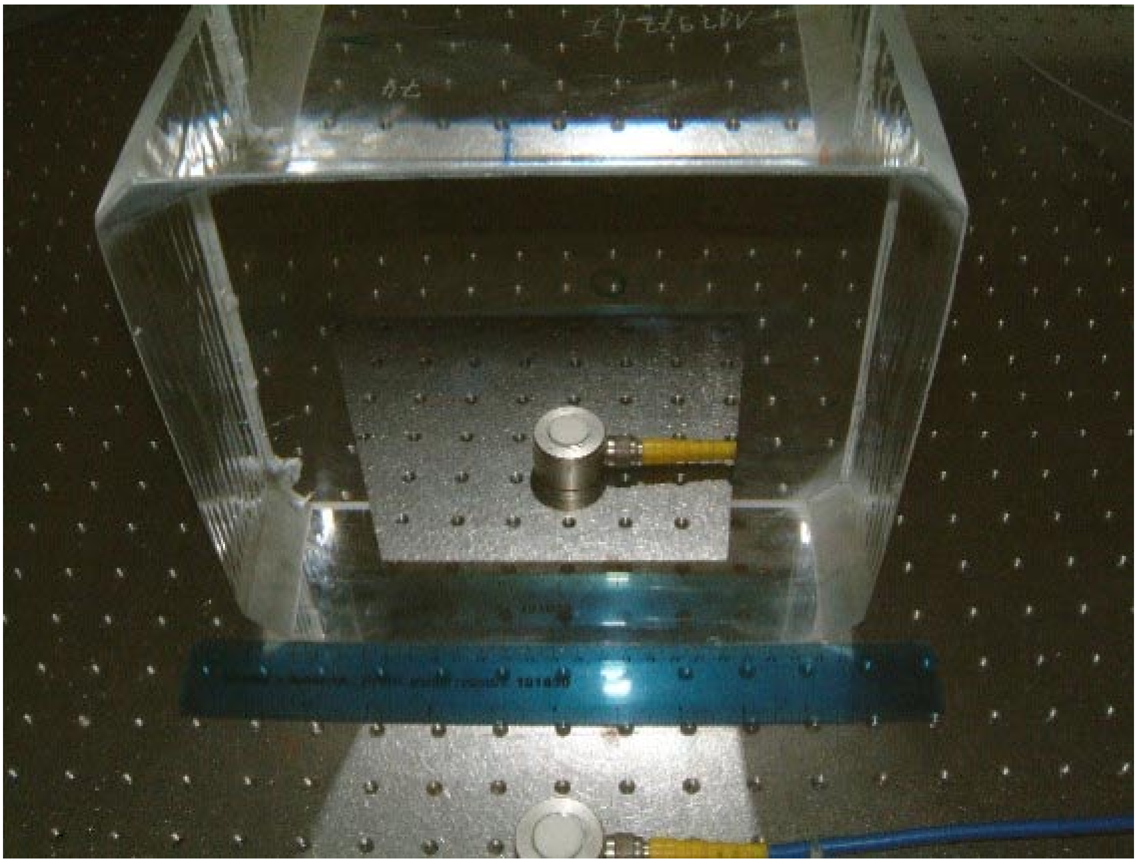

Figure 8: Acoustic emission sensor A employed for test calibrations

Each sensor was coupled to the block using the same medical ultrasound gel as was employed for the Panametrics source transducer. Signals were digitised using a Tektronix TDS 654C oscilloscope, which was triggered from the Agilent function generator. 300 time domain averages were captured for both the interferometer and acoustic emission sensor signals. The experimental method was to align the interferometer on the axis of the acoustic beam and to record the surface displacement history, having determined the reference voltage V_O for the interferometer. The AE sensor was then coupled to the block in the same position as the sensing laser beam of the interferometer and the transducer's output response to the source beam was recorded. The AE sensor or transducer output was recorded after pre-amplification as the pre-amplifier was considered an integral part of the sensor calibration. Therefore, the calibrations of sensors A and B were performed to include their associated pre-amplifier/filter units in the stated sensitivities.

Measurements were made over a range of frequencies for each transducer. In the case of sensor A, measurements were made at 20 kHz intervals over the range from 340 kHz to 580 kHz. For sensor B, the range was from 100 kHz to 200 kHz in steps of 10 kHz. 5000 data points were recorded for each waveform at all measurement frequencies with a time sampling interval of 40 ns, equivalent to a measurement bandwidth of 12.5 MHz. A time window of 70 µs duration (1750 points at 40 ns intervals) was extracted from the beginning of each data set for subsequent processing. Such a record length has the disadvantage that it is long enough to allow the return echo from the front face and the first reflections from the block sides to overlap the direct signal. However, this overlap is detected by both the AE sensor and the interferometer so that the waveforms are directly comparable. In addition, a Tukey window was used to reduce end effects in the data. All data analysis was carried out in the frequency domain and a shorter time window would have reduced the frequency resolution of the data (a 70 µs time window gives a frequency resolution of 14.286 kHz). The use of long tone bursts limits the distortion of the received signals by the AE transducer's resonance and ensures that the AE signal closely resembles the source transducer waveform. In pulsed operation the received signal is dominated by the AE sensor's resonant behaviour and the shorter time window over which the pulse exists reduces the frequency resolution. This is the reason that tone burst operation is preferred. Frequency domain analysis of the tone burst data using Fourier Transforms has the advantage that the integrating process inherent in the Transform has the effect of smoothing the data.

4.3.1 Time domain waveforms

Examples of the time domain tone burst wave forms which were obtained from the interferometer and from the AE sensors are shown below. In both cases the 480 kHz wave forms are displayed. Figures 9 to 14 display the 5000 point waveform, the 1750 point initial portion of the signal selected for subsequent processing, and the windowed 1750 point signal for both the interferometer and the AE sensor. The profile of the Tukey window, which has a ratio of constant section to tapered section of 0.5, is shown in figure 15.

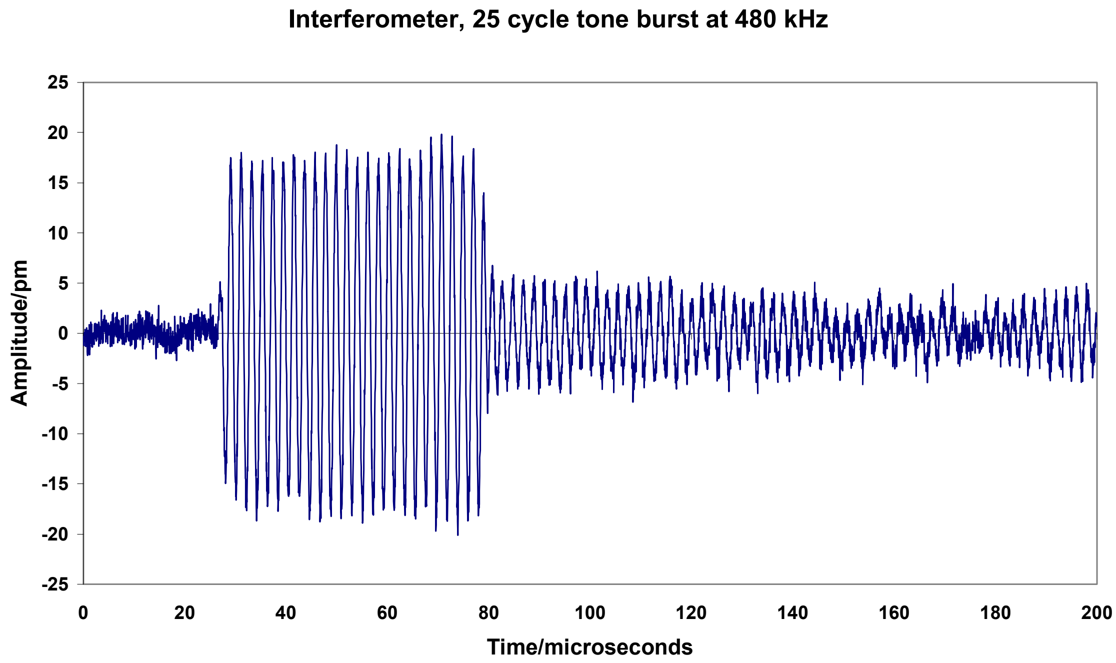

Figure 9: Interferometer time domain signal at 480 kHz

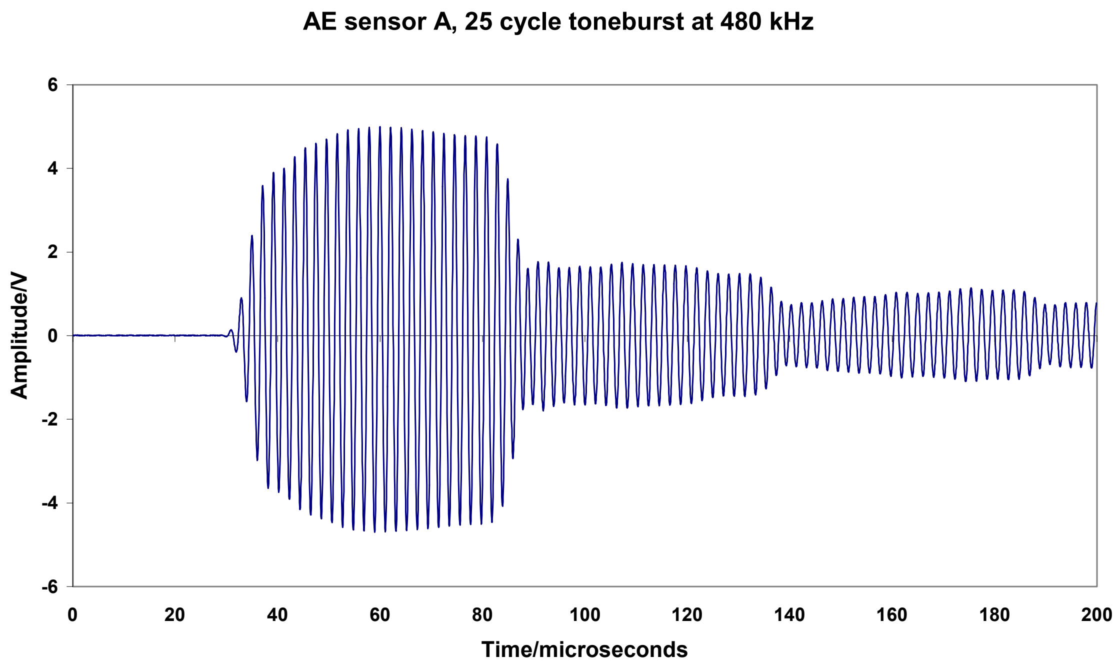

Figure 10: Acoustic emission sensor A signal at 480 kHz

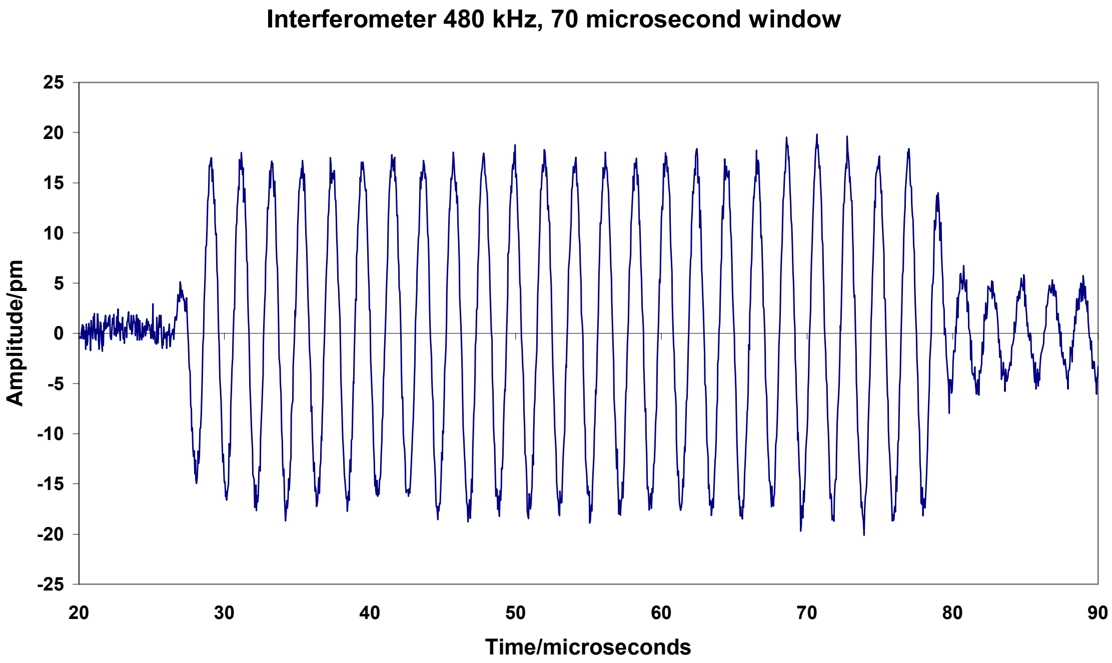

Figure 11: Interferometer, 70 μs time window

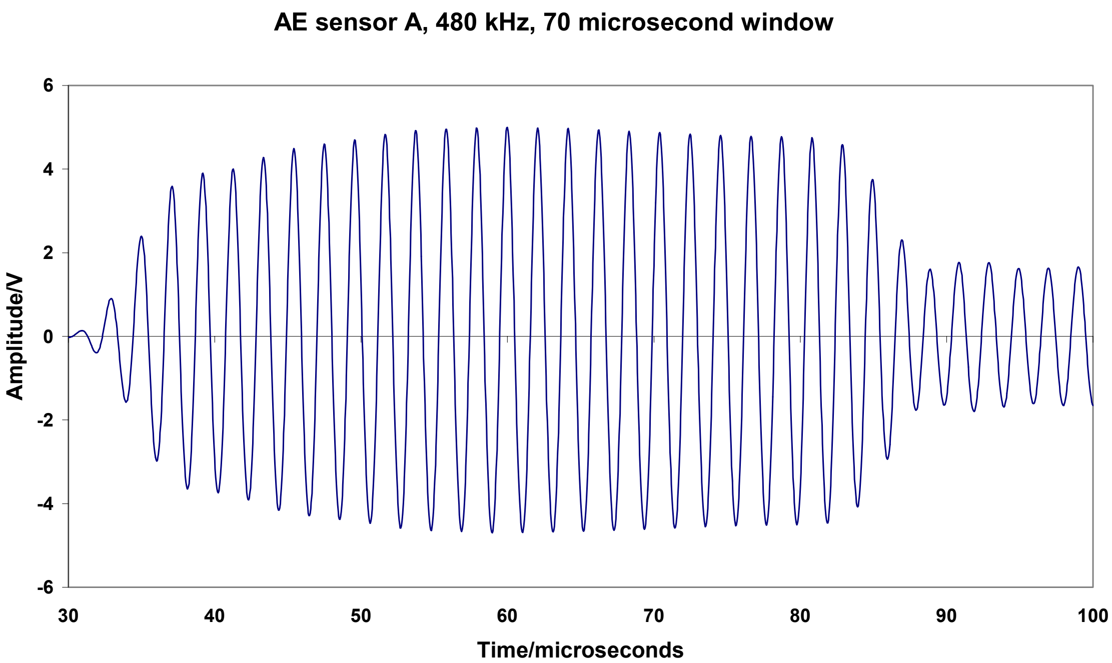

Figure 12: AE sensor A, 70 μs time window

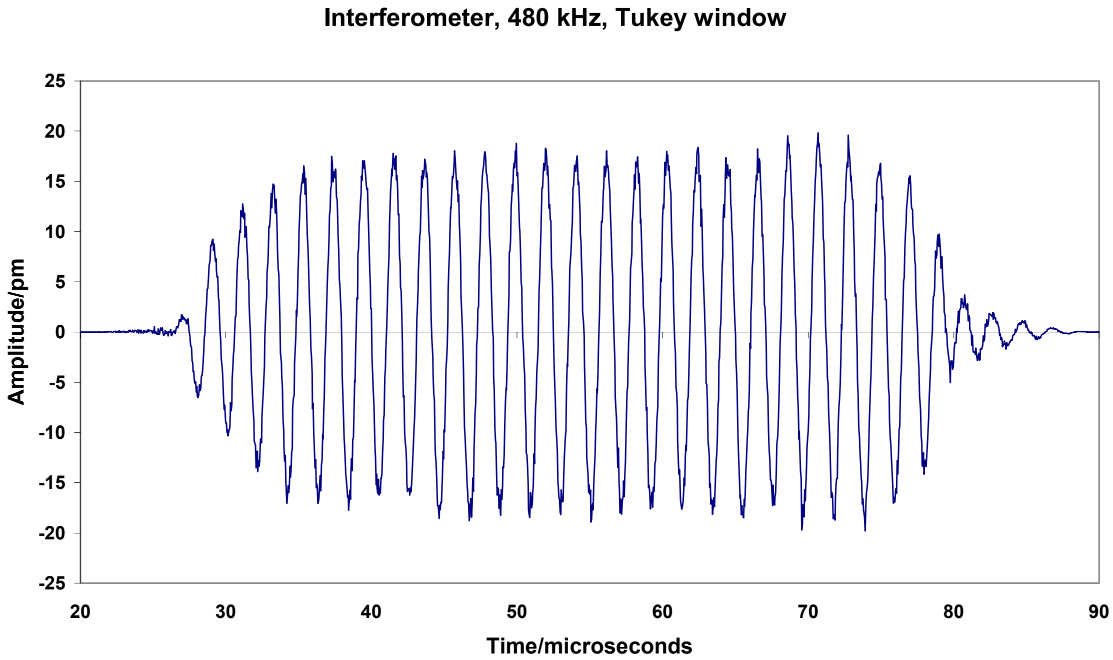

Figure 13: Interferometer 480 kHz signal after application of Tukey window

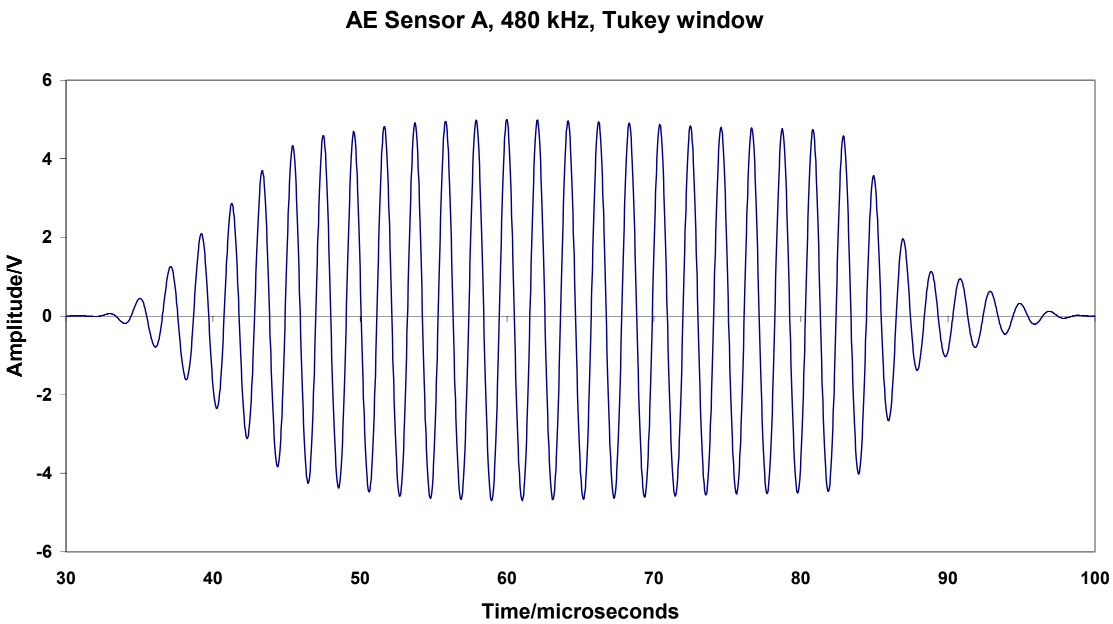

Figure 14: AE sensor A 480 kHz signal after application of Tukey window

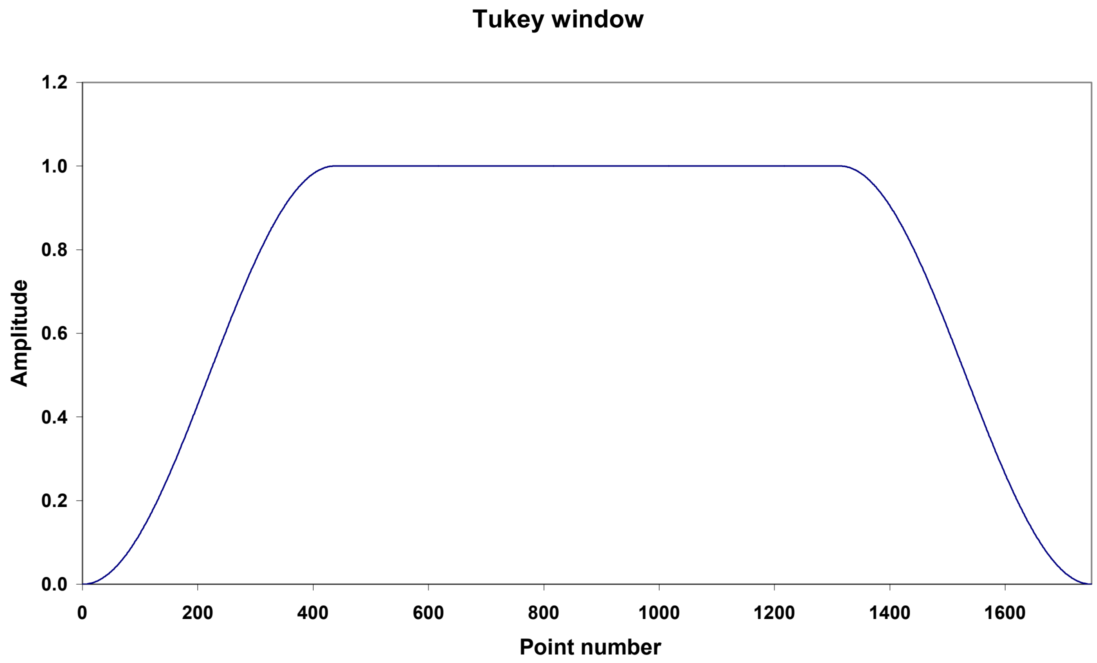

Figure 15: Profile of Tukey window used to analyse interferometer and sensor data

4.3.2 Frequency spectra: sensor A calibration

The frequency content of the signals after application of the Tukey window was analysed using the signal processing facilities of the Matlab high level programming language. The amplitude spectra of the interferometer and AE sensor signals at 480 kHz are shown in figure 16 and 17, respectively. The resolution of the discrete Fourier Transform employed in both cases is 14.286 kHz, so that the DFT returns a frequency of 486 kHz for the peak in each spectrum. Both spectra show similar features in the region of the peak frequency, suggesting that the use of the tone burst signal and subsequent windowing has substantially eliminated from the data the effect of the AE sensor's resonant behaviour.

The AE sensor's spectrum shows a second harmonic at 960 kHz, and inspection of higher frequencies shows that third and fourth harmonics are also present. This seems to be a feature of all the AE sensor spectra recorded in this series of experiments on sensor A, no matter what the frequency of the tone burst. At this stage it is not clear where the source of these higher harmonics lies. The harmonic frequencies fall outside the pass band of the acoustic emission filter and amplifier, which are designed to have a range of one octave either side of the sensor's centre frequency. If they are generated in the AE sensor itself, then what is seen in the spectra is an attenuated version of the phenomenon, owing to the effect of the band pass filter. Alternatively, they may arise in the filter and amplifier themselves. Further studies are needed to try to isolate the effect. If the sensor is behaving in a nonlinear manner, then a series of measurements with varying source signal amplitudes may help to identify the cause.

The signal distortion arising from the higher harmonics appears to be too small for it to be detectable by eye during scrutiny of the time domain sensor waveforms. Attempts to base calibrations on time domain measurements, where one needs to judge the average amplitude of a series of cycles in the tone burst, would be subject to error on account of this effect. The spectrum of the interferometer signal also shows a small peak at 100 kHz. This is present in most of the interferometer signals and seems to be interference arising from the operation of the interferometer itself. It is usually possible to identify its presence in all the time domain interferometer signals, both at the start of the time window, before the direct signal arrives, and as a modulation on the tone burst envelope.

4.3.3 Calibration results: sensor A

The calibration results were calculated from the frequency spectra obtained from the pairs of interferometer and AE sensor signals at each tone burst, following windowing of the time domain data. Ratios of the peak amplitude of the AE sensor spectrum to the peak amplitude of the interferometer spectrum were calculated for each tone burst pair. Figure 18 shows the calibration results for sensor A for the tone burst which were captured over the range from 340 kHz to 580 kHz. Figure 19 shows the peak spectral amplitudes for both the interferometer and AE sensor over the bandwidth shown in the calibration plot (figure 18). Note the same general trends in the two data sets. The two traces are best compared by considering the ratios of the maximum to minimum values in each trace, rather than by comparing absolute values. The ratio of the maximum to the minimum in the AE sensor trace is 4.04, whereas in the interferometer trace the ratio is 1.46. The lower variability in the interferometer data confirms the broad band nature of the Panametrics source transducer.

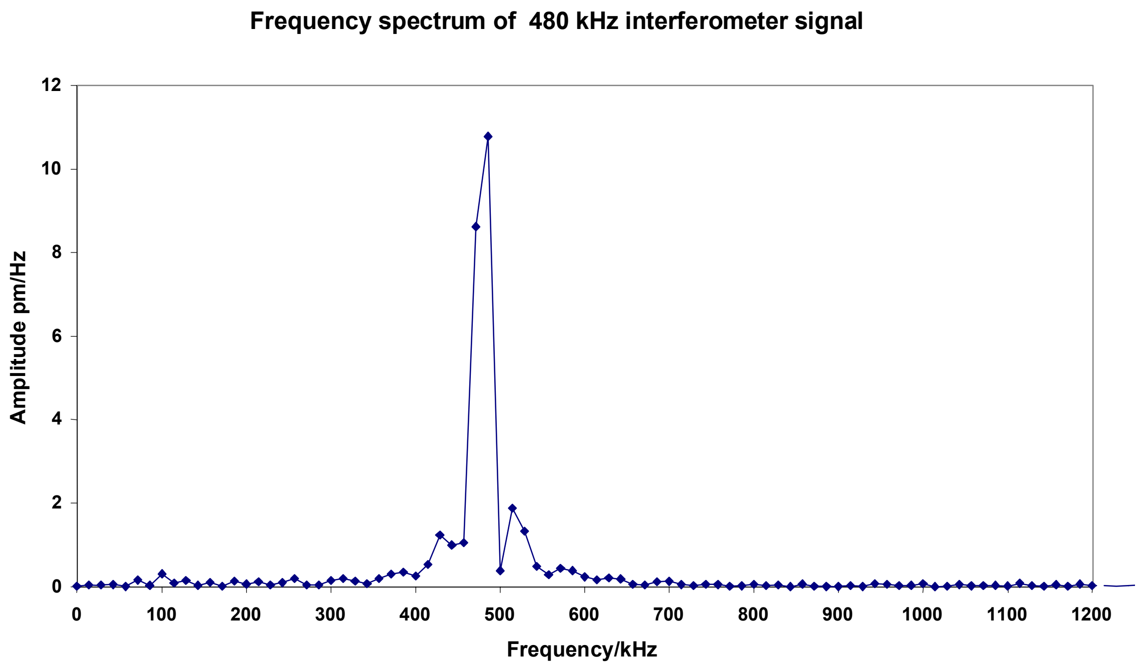

Figure 16: Frequency spectrum of 480 kHz interferometer signal

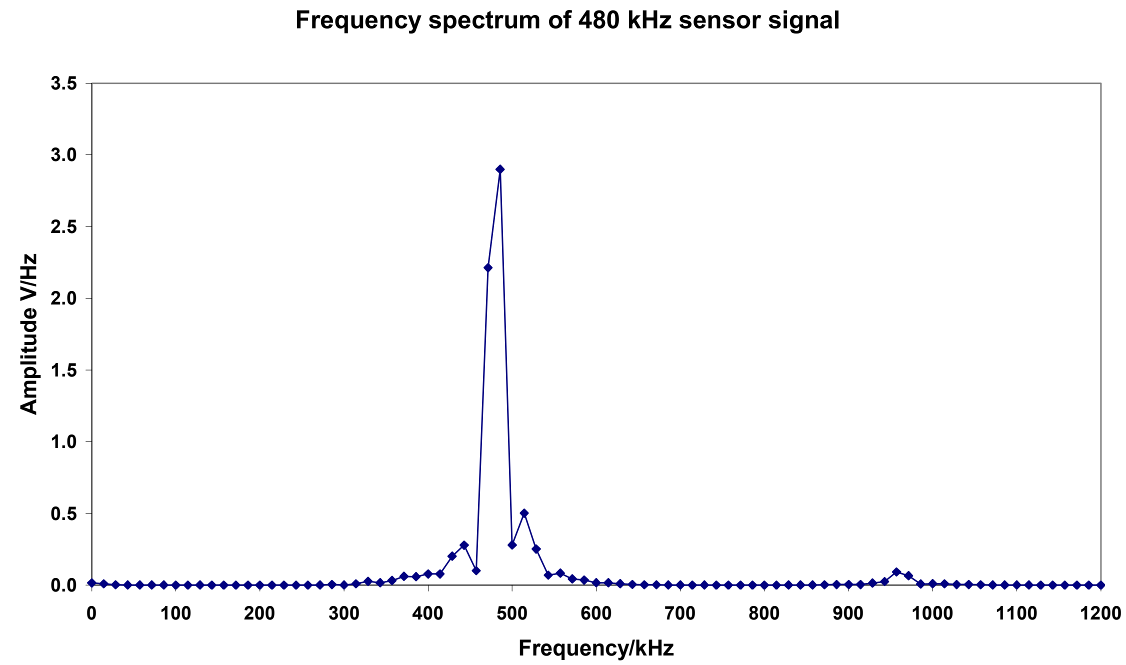

Figure 17: Frequency spectrum of 480 kHz AE sensor signal

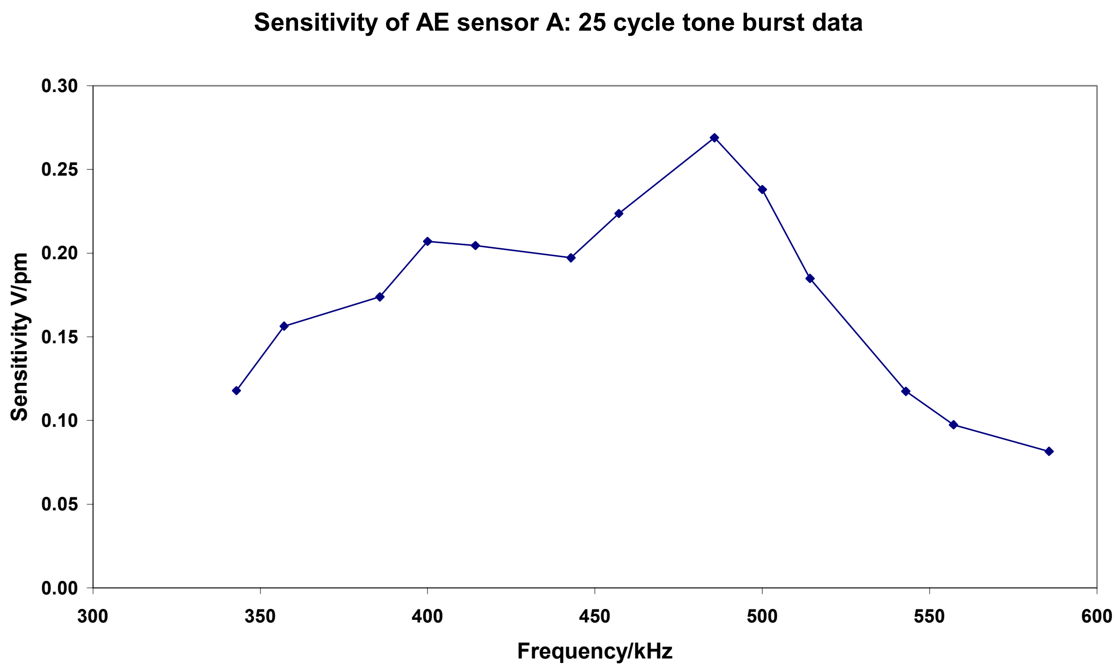

Figure 18: Sensitivity of AE sensor A in V/pm from 25 cycle tone burst data

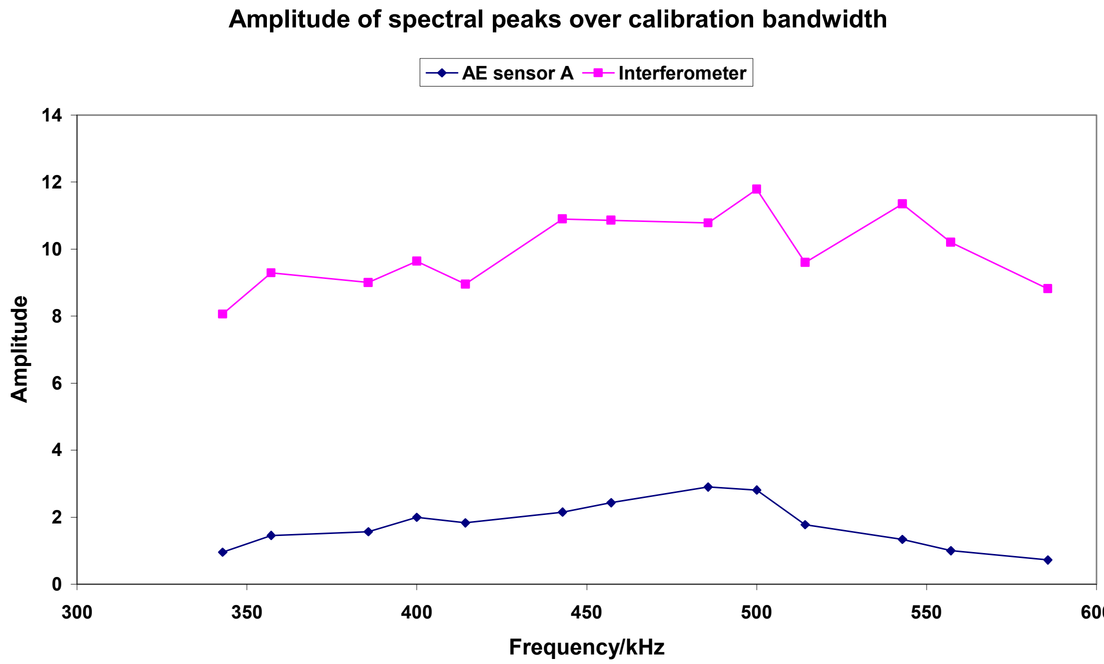

Figure 19: Compare interferometer and AE sensor A peak spectral amplitudes for 25 cycle tone burst data

4.3.4 Calibration results: sensor B

Acoustic emission sensor B was calibrated in the same manner as sensor A. All time sampling intervals, record lengths, window duration and shapes were kept the same as for the calibration of sensor A. The only difference was that the range of the 25 cycle tone bursts was from 100 kHz to 200 kHz in intervals of 10 kHz. As all record and window lengths remained unchanged from the sensor A measurements, the main difference between the two calibrations is that fewer cycles of the tone burst were used in the analysis of the sensor B results. The resolution of the discrete Fourier Transform remained the same at 14.286 kHz but the tone burst intervals were 10 kHz. Thus there were eleven pairs of measurements over the bandwidth 100 kHz to 200 kHz, but the DFT only allowed the data to be analysed over eight discrete frequencies, so that occasionally successive nominal tone burst frequencies produced DFT data at the same discrete frequency value. Where this occurred the pairs of values at the same frequency were averaged before the sensitivity of sensor B was calculated.

Figures 20 and 21 show the frequency spectra obtained from the 160 kHz tone burst for the interferometer and sensor B respectively. Once again, note the general similarity of the two spectra. Figure 22 is the sensitivity of AE sensor B as a function of frequency over the range from 100 kHz to 200 kHz and figure 23 compares the amplitude of the spectral peaks recorded for the interferometer and the AE sensor at each calibration point. The ratio of maximum peak amplitude to minimum peak amplitude is 2.03 for the interferometer and 6.82 for the acoustic emission sensor.

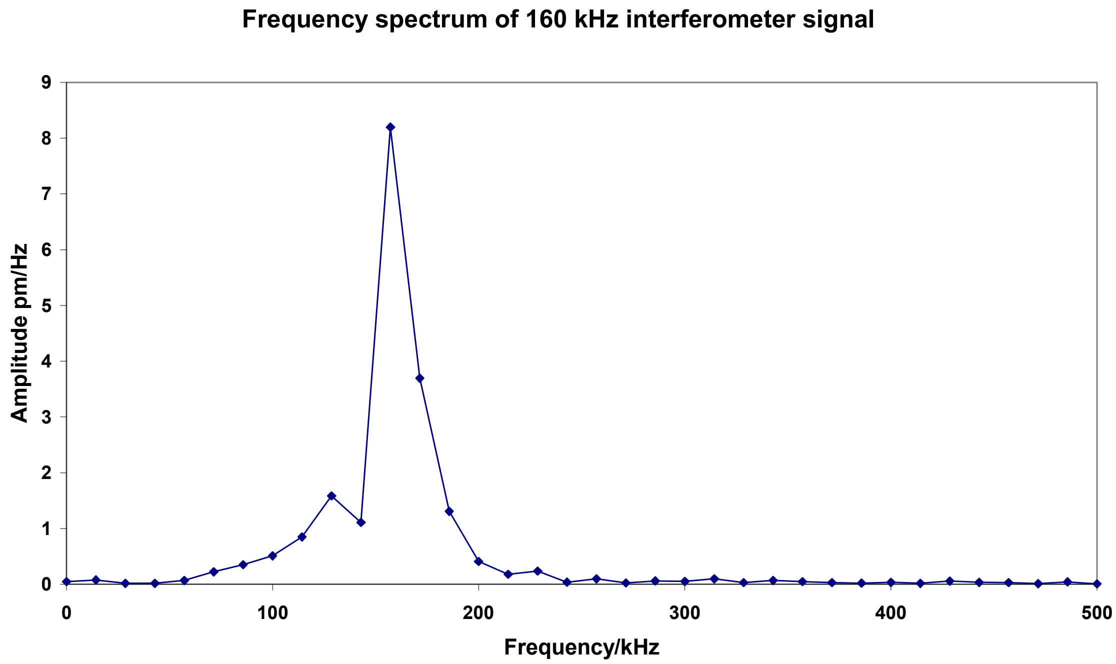

Figure 20: Frequency spectrum of 160 kHz interferometer signal

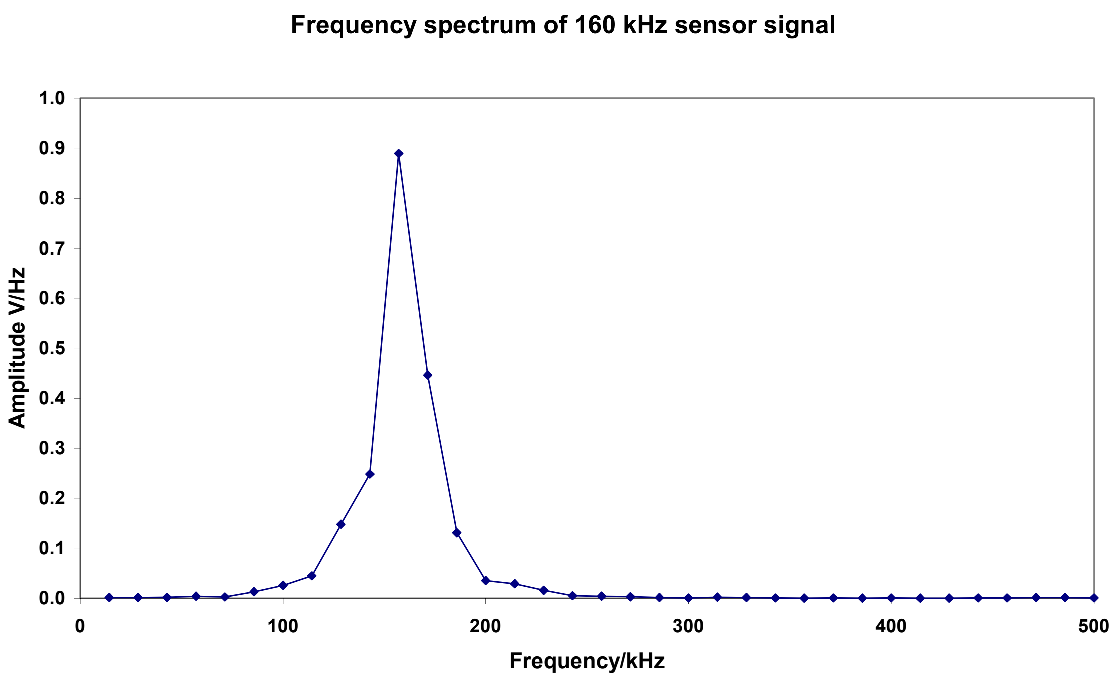

Figure 21: Frequency spectrum of 160 kHz AE sensor B signal

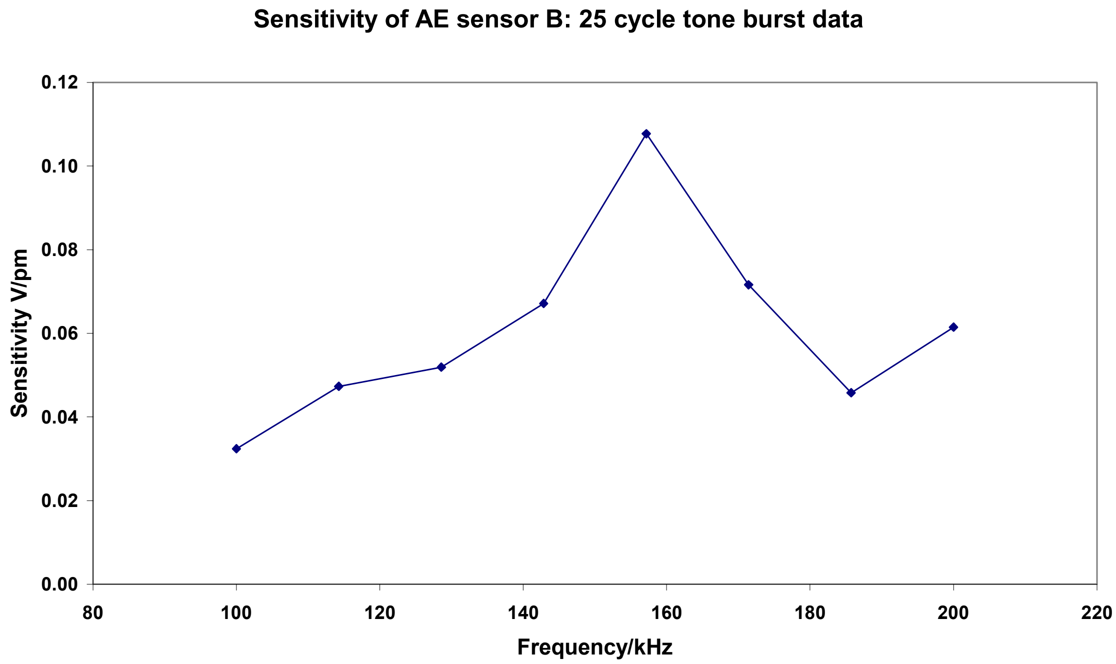

Figure 22: Sensitivity of AE sensor B in V/pm from 25 cycle tone burst data

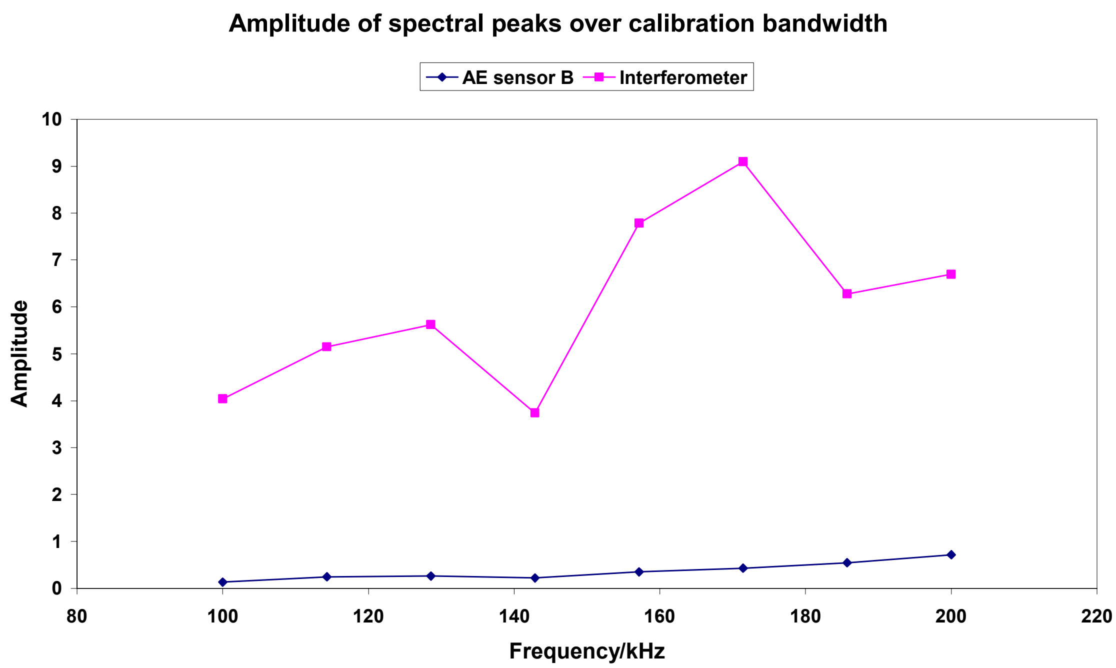

Figure 23: Compare interferometer and AE sensor B peak spectral amplitudes for 25 cycle tone burst data

4.3.5 Coupling variations

A series of repeat calibrations of sensor A was carried out to determine the variability introduced into the calibration by uncoupling and recoupling the transducer undergoing calibration. The method employed was identical to that used for the initial calibration reported above, except that the AE sensor was removed from the test block and re-coupled for a series of four measurements. Only one determination of displacement was made with the interferometer and this interferometer data set was used for the calculation of sensor sensitivity in all four cases. In addition, data were collected at 10 kHz nominal frequency intervals, rather than the 20 kHz intervals employed for the earlier work.

The analysis of the calibration data differed from that carried out for the initial calibrations in two respects. A longer Tukey window was employed (2000 points) giving a DFT resolution of 12.5 kHz. Secondly, it had been noted in the earlier work that the limited DFT resolution and the presence of a range of frequencies in the measurement data, often led to "split" or "blunt" peaks in the frequency spectra of both the sensor and the interferometer signal. Instead of identifying a single peak maximum value in the data for the calculation of the sensor sensitivity it was decided to include the peak frequency value and the frequency values either side of the peak value in the calibration. As the nominal frequency interval for the tone bursts was 10 kHz and the resolution of the DFT was 12.5 kHz this meant that there was almost always more than one calibration value, and frequently up to four calibration values available at each frequency step. The results were plotted on scatter diagrams so that the range of values at each calibration are available. The four repeat calibrations are shown in figures 24 to 27.

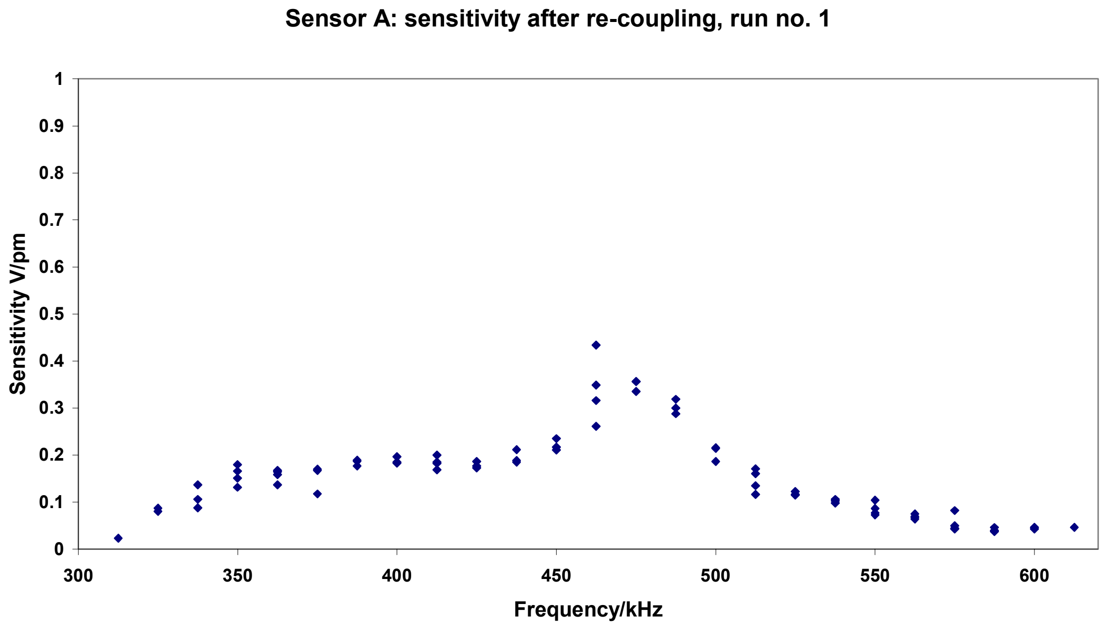

Figure 24: Sensitivity of sensor A after initial re-coupling

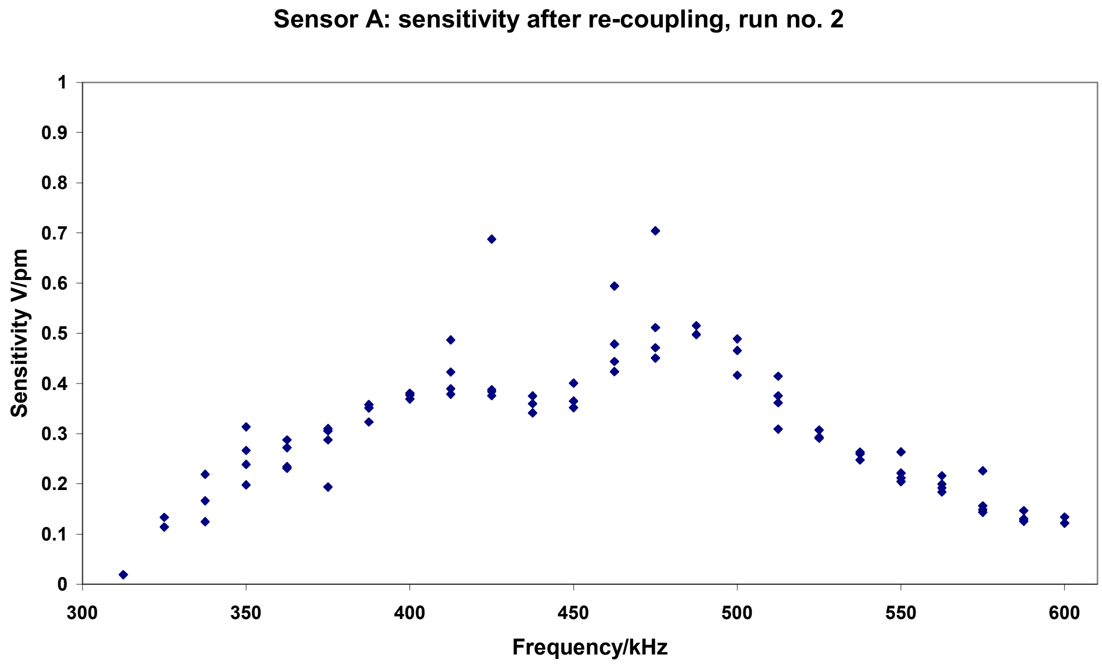

Figure 25: Sensitivity of sensor A after second re-coupling

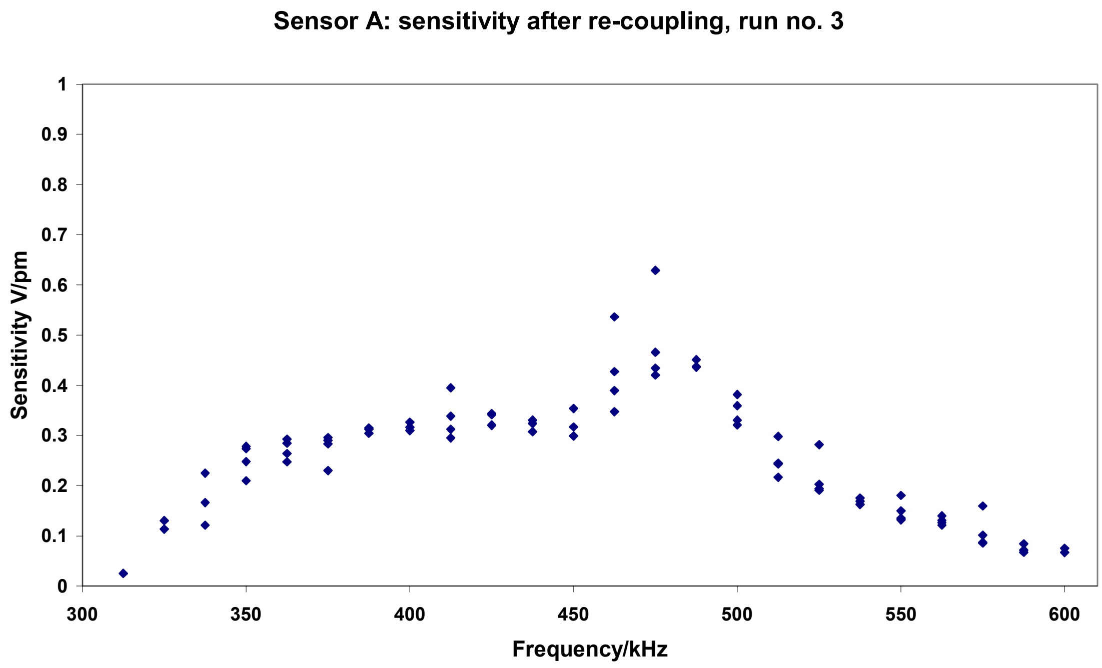

Figure 26: Sensitivity of sensor A after third re-coupling

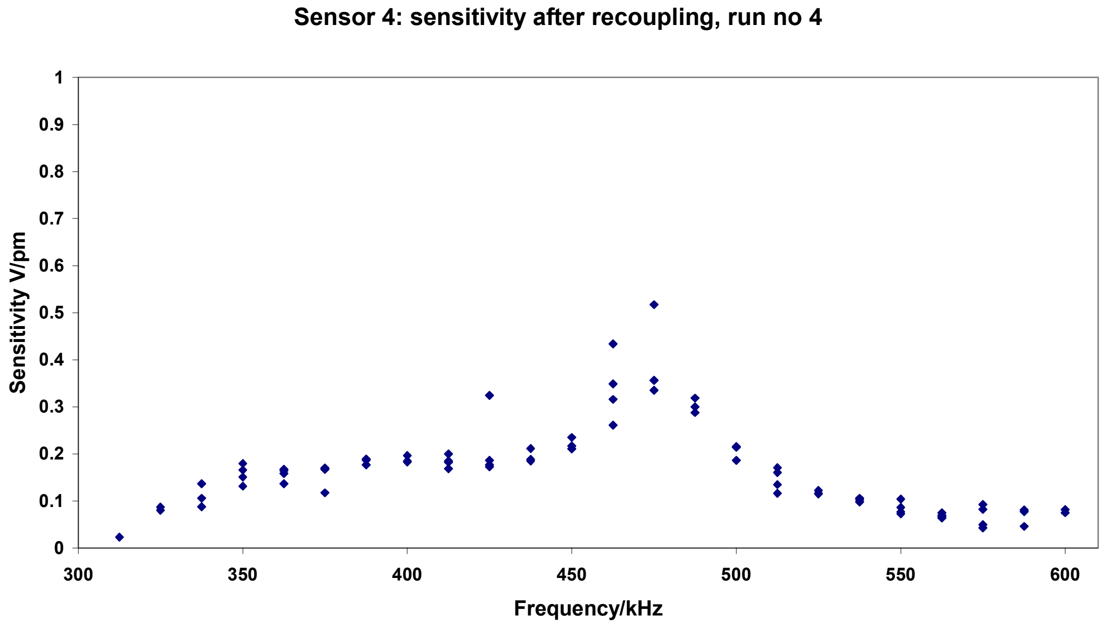

Figure 27: Sensitivity of sensor A after fourth re-coupling

Although the sensitivity of sensor A retains approximately the same shape profile over the bandwidth of the calibration, the absolute values vary by a factor of approximately two in many cases. At the peak sensitivities, between 450 kHz and 500 kHz, it could be argued that several of the higher values should be disregarded as outliers. However, outside this frequency range, where the scatter of the data points is reduced, at 400 kHz for example, the absolute values of the calibration sensitivities vary from 0.18 V/pm in the fourth run to 0.37 V/pm in the second run.

The main reasons for this coupling variability seem to be associated with the requirement of performing the calibration on that region of the glass block which has been coated with soft aluminium. Owing to the need not to damage the aluminium so that future interferometer measurements are not compromised, and the fact that the aluminium coating itself prevents a visual check of the sensor face to ensure that no visible bubbles are present, it is difficult to maintain consistent coupling from one measurement to the next. To test this, it was decided to compare the repeatability of coupling when the sensor was located directly on the glass surface, away from the region of aluminium coating. For this experiment the source transducer was kept fixed in the same position and the sensor was uncoupled and re-coupled seven times, with care being taken to ensure that a consistent level of force was applied to the transducer and that the coupling gel and sensor face were free of visible bubbles. The time domain traces recorded from the sensor for a 480 kHz 25-cycle tone bursts were then compared. Examination of the time domain traces shows that in this case a high level of repeatability was achieved. This is demonstrated by figures 28 and 29 which show successive wave forms obtained when the sensor was uncoupled and re-coupled to the glass surface of the block.

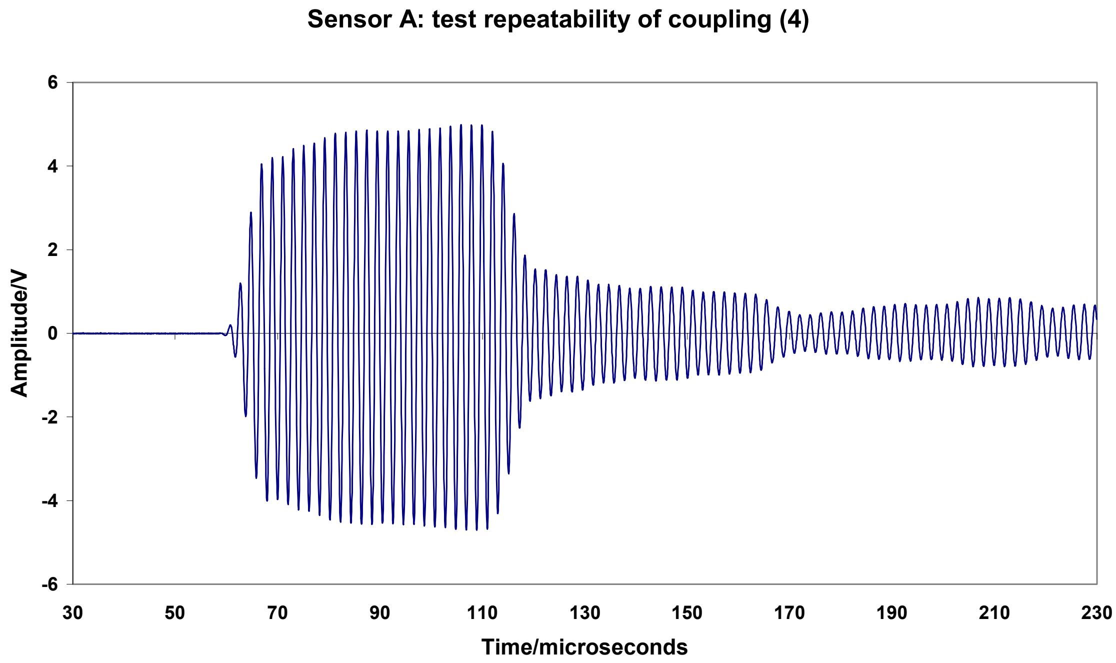

Figure 28: 480 kHz time domain trace for sensor A, measured on glass surface of test block, example 1

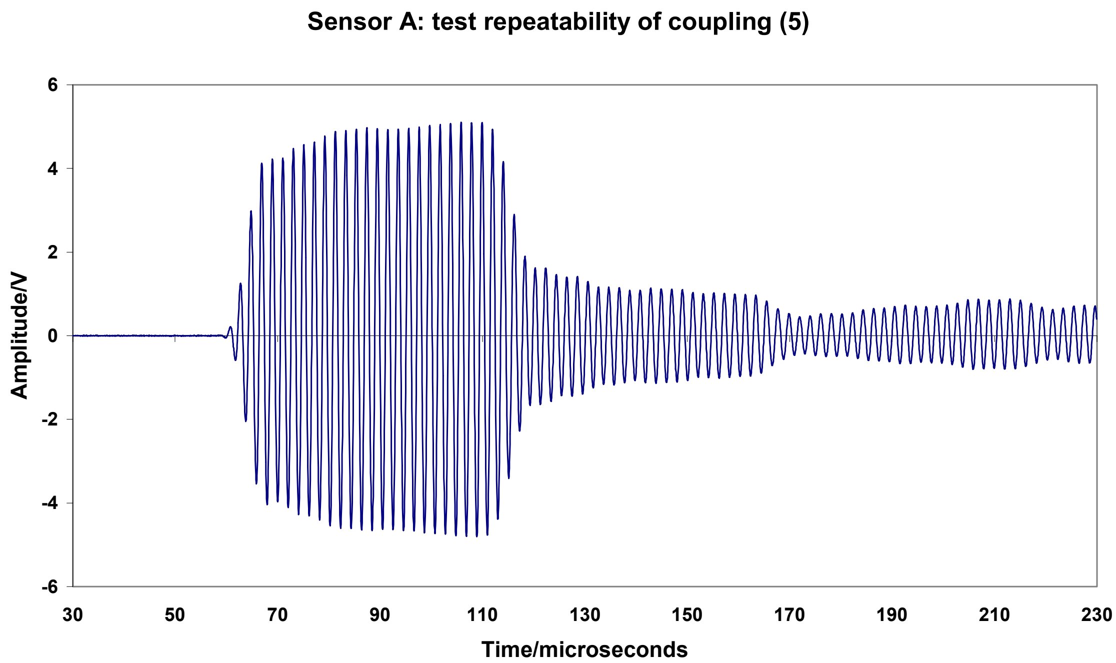

Figure 29: 480 kHz time domain trace for sensor A, measured on glass surface of test block, example 2

Recoupling the source transducer poses fewer problems than recoupling the sensor. The source transducer is always coupled directly to a glass surface so that it is always possible to perform a visual check of the transducer's front face. Re-coupling tests of the source transducer show at least the same level of repeatability as was achieved for the sensor when it was coupled to a glass surface. To eliminate the coupling variability observed in the four repeat calibrations described above, two methods suggest themselves. The first is to be willing to risk damage to the soft aluminium coating during calibration by applying a consistent but substantial force to the sensor under test. This may require a range of mounting techniques, jigs or fixtures depending on the size and shape of the AE sensors to be tested. The soft coating may need to be renewed more frequently in this case, and the costs of this would form part of the costs of maintaining a calibration service for acoustic emission sensors. An alternative approach is to calibrate a broad band transducer against the interferometer on the aluminium coated surface and to regard this as a primary calibration. Customers' AE sensors could then be calibrated against the broad band transducer directly onto a glass surface rather on the aluminium coating.

4.4 SIGNAL PROCESSING UNCERTAINTIES: SELECTING WINDOWING PARAMETERS

The technique used for determining the sensitivity of the AE sensor requires the time domain signal to be windowed before processing in the frequency domain. The window used in the work reported earlier in this chapter has been a Tukey window with a taper ratio of 0.5 and a length of either 1750 or 2000 data points to give the best possible frequency spectral resolution after applying the Fourier Transform. To establish the effect of the chosen window parameters on the time domain signal and thus their effect on the sensitivity of the transducer, three window parameters have been investigated as follows:

1. The window taper ratio for a fixed length (1250 data points) and fixed position centred between the first and second arrivals of the direct compressional wave propagating through the block.
2. The window length for a fixed ratio of 0.5 and a fixed position centred between the first and second arrivals of the direct compressional wave propagating through the block.
3. The window position in the time domain signal for a fixed taper ratio of 0.5 and a fixed length of 1250 data points.

The data set used for the investigation was that obtained from the calibration of sensor A during the investigation of re-coupling issues (run no. 1: see figure 24 for the calibration results from this run), with frequencies of 480 kHz and 540 kHz being used to represent signals at the resonant frequency of the sensor and away from the resonant frequency respectively.

4.4.1 Window ratio

The Tukey window has been investigated as applied to this data set for taper ratios of 0.1 to 1 at 0.1 intervals, where zero represents a rectangular window and 1 represents a Hanning window. A fixed window length of 1250 data points or 50 µs was used, centred around a point directly between the arrival of the first compressional wave and the first reflection from the opposite face of the glass test block. The time interval between the first arrival and the direct reflection is approximately 53 µs. The consequence of the window length being shorter than the interval between the echoes means that the start of the first arrival and the end of the second arrival are windowed out of the frequency analysis. The beginning of each arrival (both the direct signal and the first reflection) is dominated by the resonance of the AE sensor, even when the discrete tone burst is not centred at this frequency. The tapering of the window therefore, helps to reduce the contribution of this resonant component when tone bursts are used that are not centred at the resonant frequency of the sensor. Figures 30 and 31 show the calculated AE sensor sensitivity as a function of the taper ratio of the Tukey window. The sensitivity of the transducer shows a greater change with the window taper ratio for the 540 kHz tone burst which is higher than the sensor's resonant frequency of approximately 480 kHz, than it does with the tone burst centred at 480 kHz. The sensor sensitivity as shown in figures 30 and 31, is derived from the peak amplitude in the frequency domain of the windowed signals. As the flat portion of the window becomes narrower (ratio $\rightarrow$ 1) the contribution from the resonant components immediately following the arrival of the compressional wave or its reflection is reduced and this manifests as a decrease in the sensitivity of the sensor at the frequency of interest. The effect is less noticeable for the 480 kHz signal since the sensor is actually being excited close to its resonant frequency.

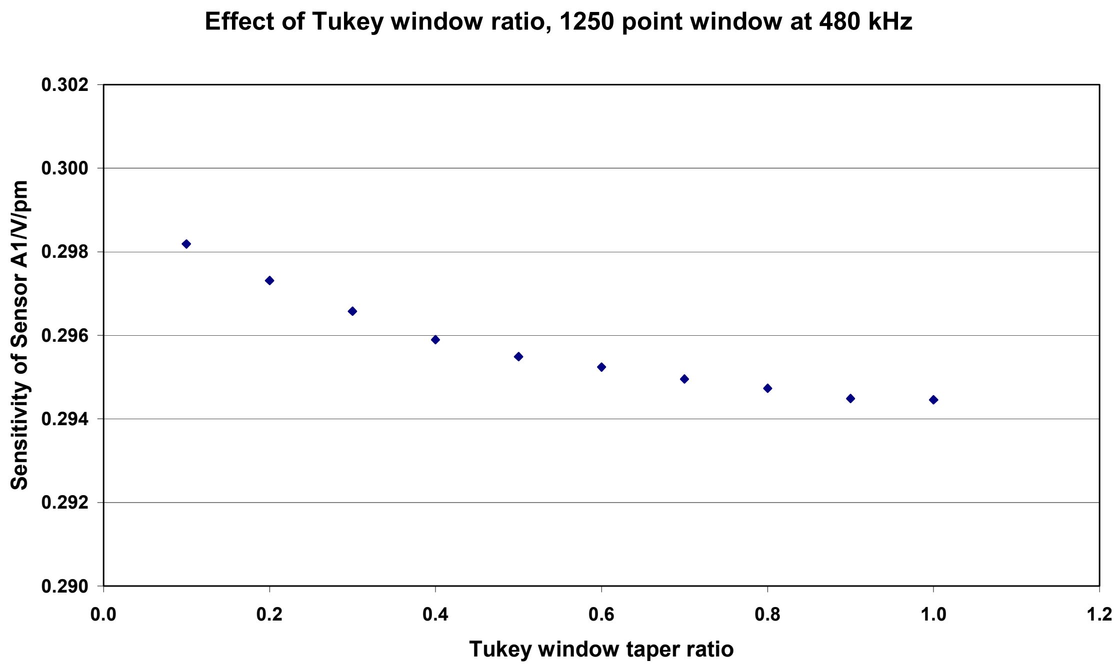

Figure 30: Effect of Tukey window taper ratio on sensitivity at 480 kHz

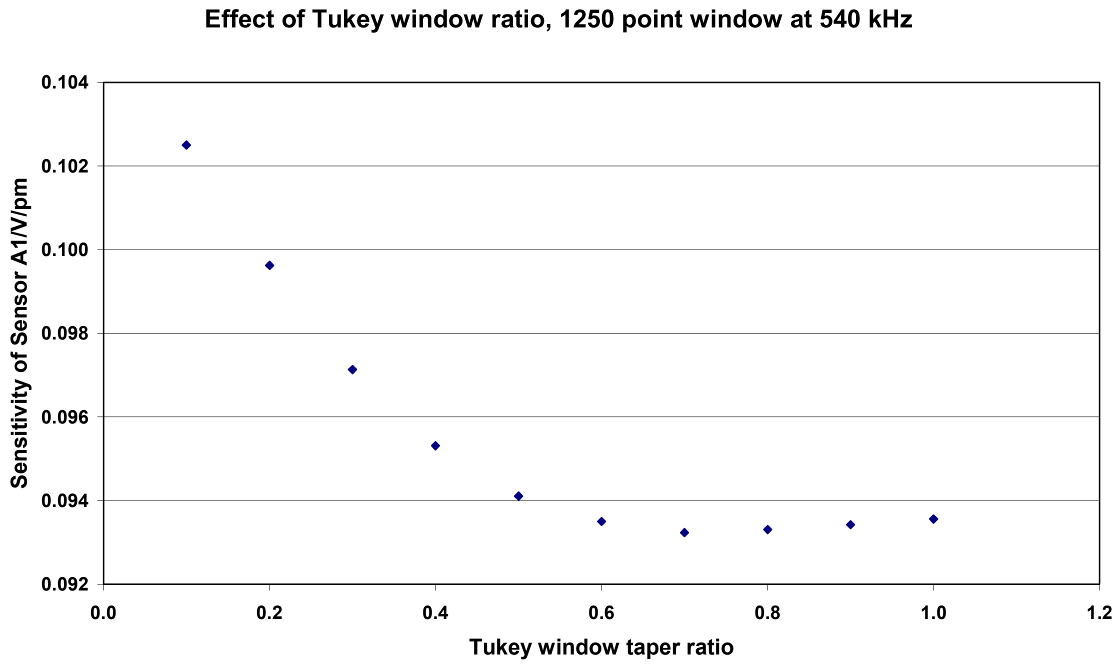

Figure 31: Effect of Tukey window taper ratio on sensitivity at 540 kHz

The window taper ratio can be seen to cause a variation in sensitivity of up to 10%. However, it is the central portion of the time domain signal that is of interest. This ensures that the sensitivity of the sensor is determined when it has settled out of resonance and before the first reflection occurs. A taper ratio between 0.5 and 0.6 is therefore required to reduce the contributions at the edge of the window where the signal represents resonance in the sensor. Any choice of ratio around this range would lead only to a small variation in the established sensitivity of the sensor.

4.4.2 Window length

The window length was investigated for a fixed position centred directly between the first arrival of the compressional wave and its first back reflection. The window lengths used were 500, 1000, 1250, 1500 and 2000 data points or 20 µs, 40 µs, 50 µs, 60 µs and 80 µs respectively. The tone burst length at 480 kHz was approximately 52 µs and at 540 kHz it was approximately 46 µs. The time interval between the first arrival and the first reflection from the opposite face of the block was approximately 53 µs, therefore both the windows of length 1500 and 2000 data points contain information that was not necessarily part of the signal from the tone burst. The advantage of using a window longer than the interval between arrivals was the better resolution obtained when analysing in the frequency domain. The calibration effectively uses the steady state response of the sensor and it was therefore preferable to use a shorter window that excludes the information contained at the start of the tone burst before the sensor reaches its steady state. Figures 32 and 33 show the effect of the window length on the sensitivity of the AE sensor, where identical windows were applied to the interferometer and the sensor time data.

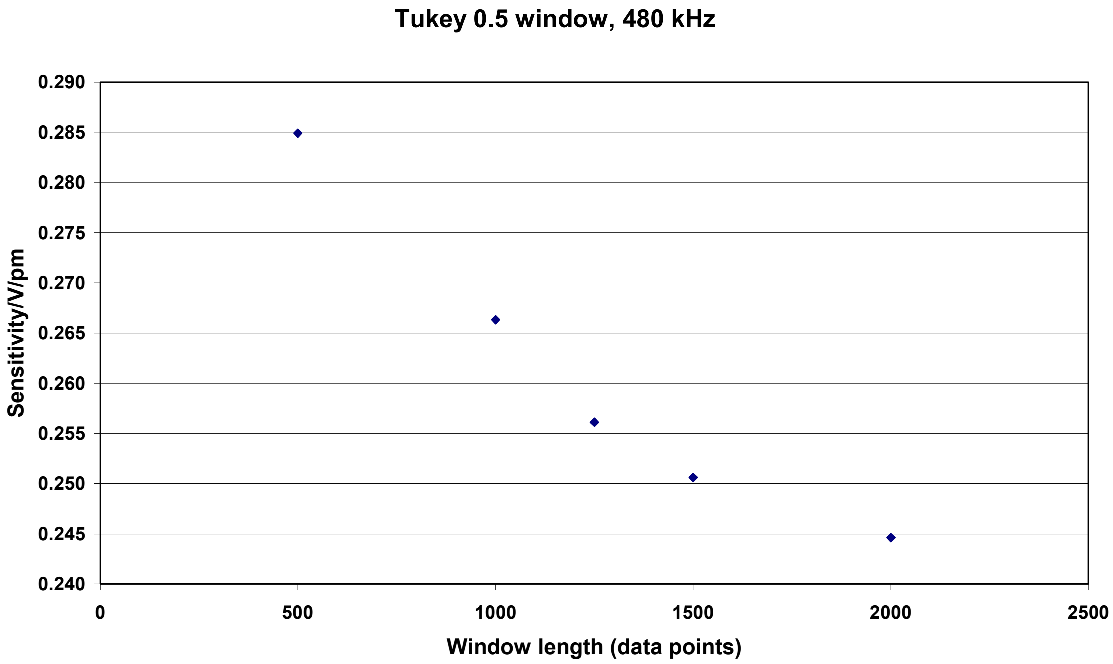

Figure 32: Effect of Tukey window length on sensitivity at 480 kHz

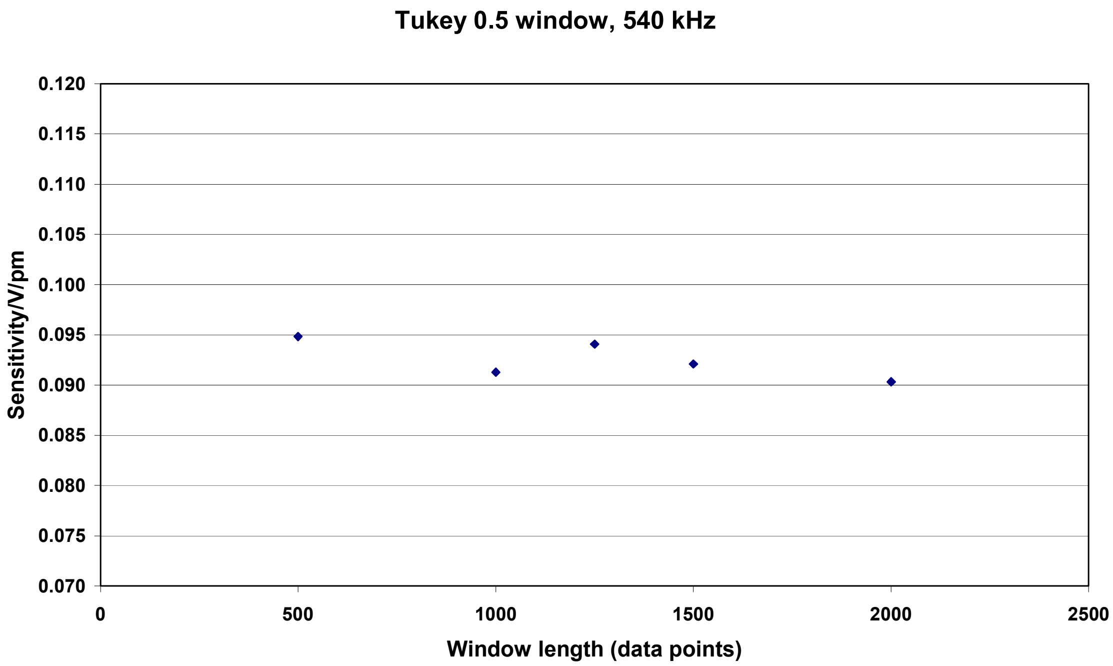

Figure 33: Effect of Tukey window length on sensitivity at 540 kHz

These figures show that an uncertainty of up to 15% could result with poor selection of the window length. The reason for the negative gradient in figure 32 was due to the fact that the interferometer signal has a flat amplitude response across the length of the tone burst, where the sensor does not. For the case of the sensor, increasing the length of the window, generally leads to a lower average amplitude owing to the time taken for the sensor to rise to its resonance and reach a steady state. In figure 33 this was not the case, since the sensor achieves a steady state at 540 kHz. The resonance observed in this case, before the sensor achieves a steady state, was dominant and therefore only a small decrease in average amplitude was observed.

4.4.3 Window position

The effect of window position has been investigated by positioning a fixed length window of 1250 data points and of fixed taper ratio of 0.5 at different locations around the centre point of the received tone burst. The window was moved in 100 data point (4 µs) steps to observe the effects of moving the window either side of the first arrival and the first reflection, where the resonant effect is most significant. The results shown in figures 34 and 35 show the calculated sensitivity of the AE sensor as a function of the window position, where the window position is stated as a relative value that indicates the position of the centre of the window relative to the central point between echoes in the waveform. These figures help to find the optimum position of the window, so that the resonance of the sensor does not dominate, or that the rise of the sensor signal does not greatly influence the calculated sensitivity. Therefore the window would ideally be positioned where the rate of change of sensitivity is least significant.

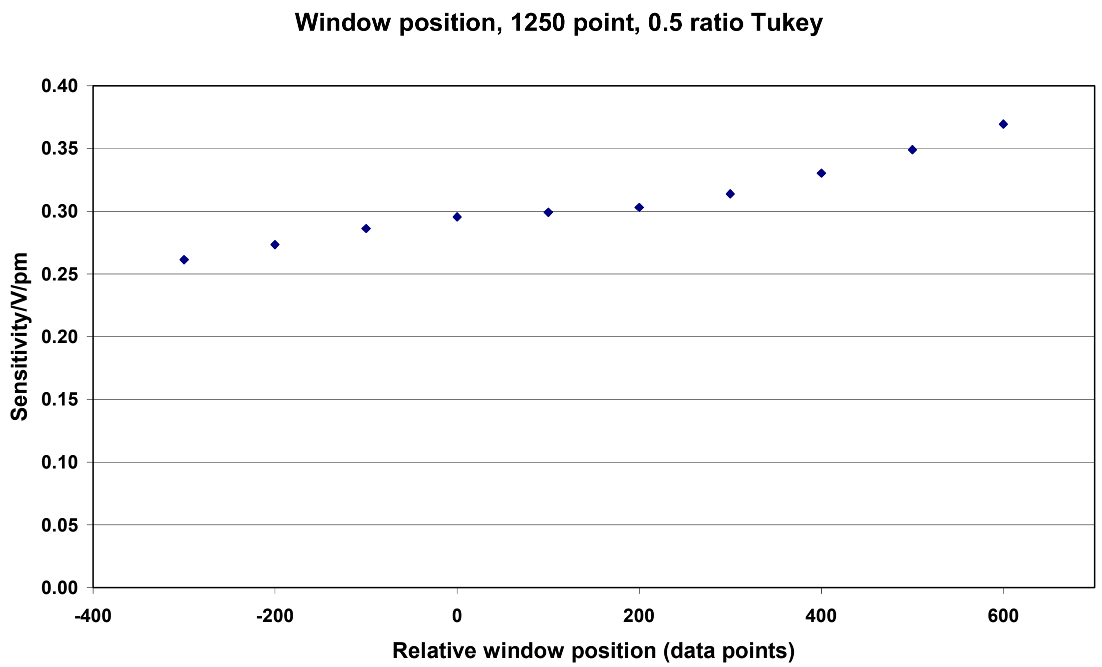

Figure 34: Effect of window position on sensitivity at 480 kHz

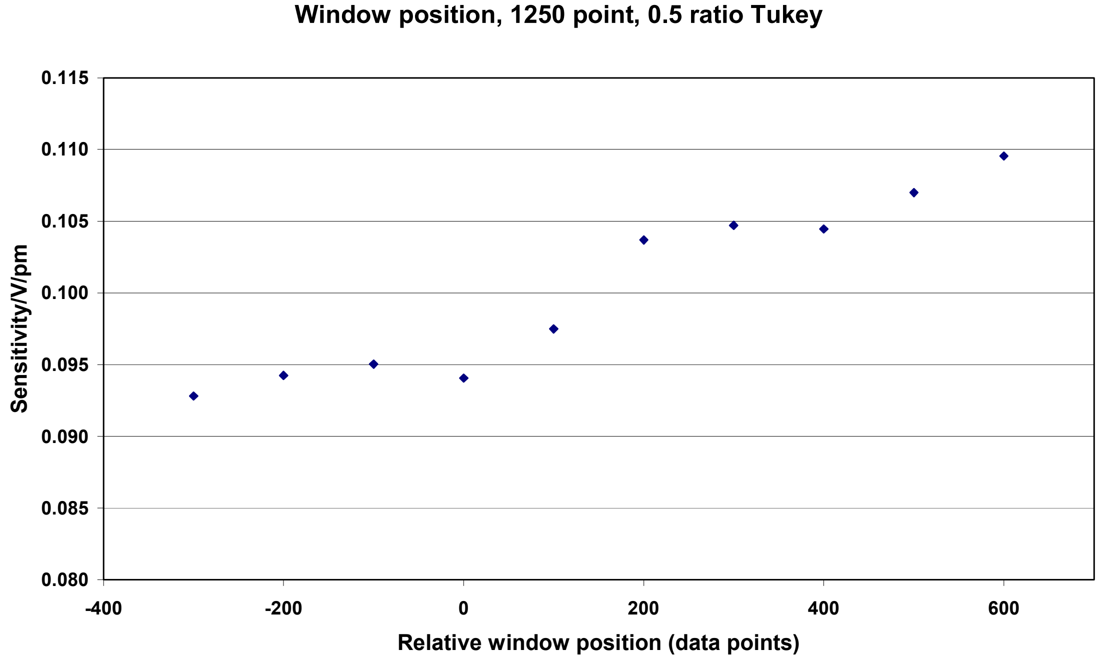

Figure 35: Effect of window position on sensitivity at 540 kHz.

The use of a window before performing the frequency analysis, although essential to remove end effects in the DFT, does in fact introduce its own artefacts into the original waveform. This means that careful selection of the windowing method is necessary and the calibration methodology is rather subjective to a suitable choice of window parameters. The reason for this is essentially that the useable length of the data set is too short and the sensor signal is not always in a steady state for a long enough period between the first arrival and the first reflection. The uncertainties due to the subjective nature of the signal processing can give rise to variations in AE sensor sensitivity of around 15%, which is likely to be the largest single contribution to the uncertainty budget if repeatability problems arising from coupling variability can be overcome. The above analysis leads to the conclusion that it would be preferable to work with a much larger test block, so that a longer time window, free from the effects of transients and reflections is available. Calibrations at lower frequencies on the current block are likely to show even more sensitivity to signal processing techniques than those at the higher frequencies analysed here.

4.5 TIME/FREQUENCY ANALYSIS

A clear picture of the nature of the windowing problem and of the difference between the sensor and interferometer waveforms is provided by a time/frequency or spectrogram analysis of the measured signals for 320 kHz, 480 kHz and 540 kHz for sensor A, together with the associated interferometer signals. The analysis was performed using the Matlab high-level computing language. In each case the data were analysed by passing a 512-point Tukey window across the 5000-point data sets with a 400-point overlap from one windowed segment to the next and displaying the frequency content of each successive time window. In all cases the time sampling interval was 40 ns, a sampling frequency of 25 MHz.

The results are presented in figures 36 to 41. The ranges of the displayed data have been restricted to 0 to 2 MHz along the frequency axis, and from 0 to 150 microseconds on the time axis. The colour coding indicates the amplitude of the frequency component at each time step, where the reds and browns represent high amplitudes and the blues represent low amplitudes.

The spectrograms have a number of important features.

1. Both the sensor and interferometer plots show higher harmonics of the tone burst frequency. This is most noticeable in the 540 kHz sensor plot.
2. The interferometer plots are considerably noisier than the sensor plots.
3. The start of the direct signal and the first echo are "smeared out" by the sensor's resonant response, which makes the location of key features harder to detect than in the interferometer signals.

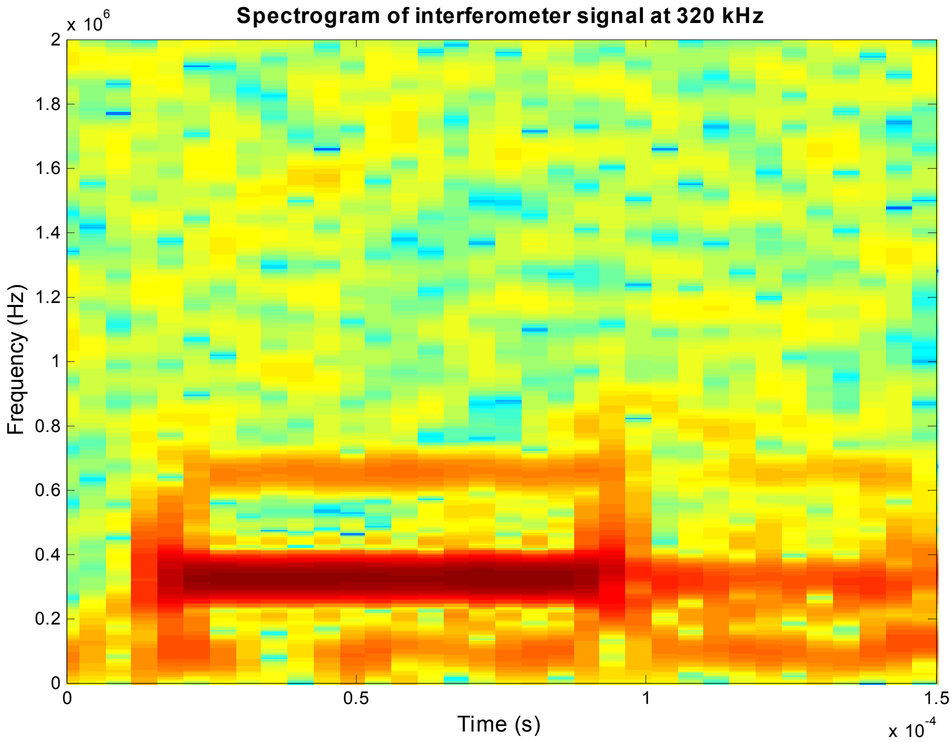

Figure 36: Interferometer spectrogram at 320 kHz

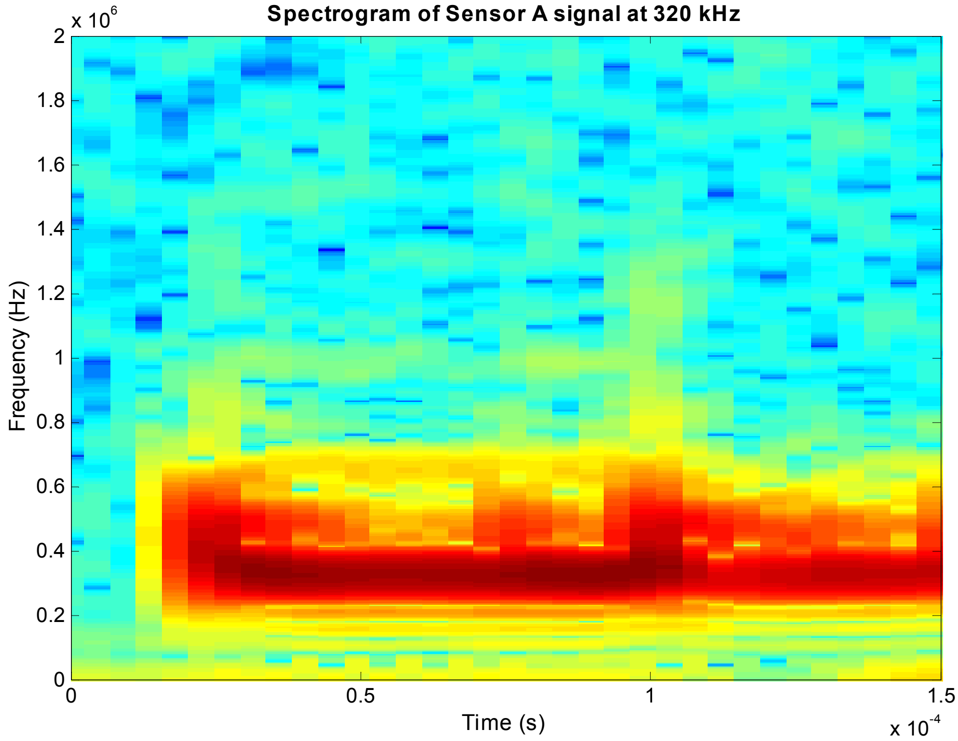

Figure 37: AE sensor spectrogram at 320 kHz

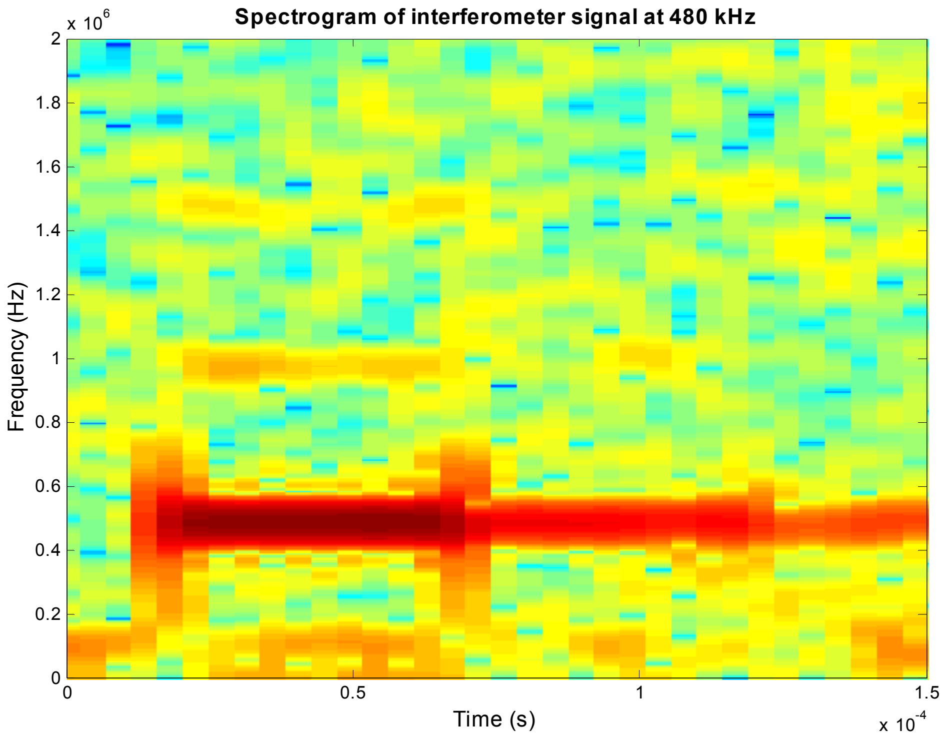

Figure 38: Interferometer spectrogram at 480 kHz

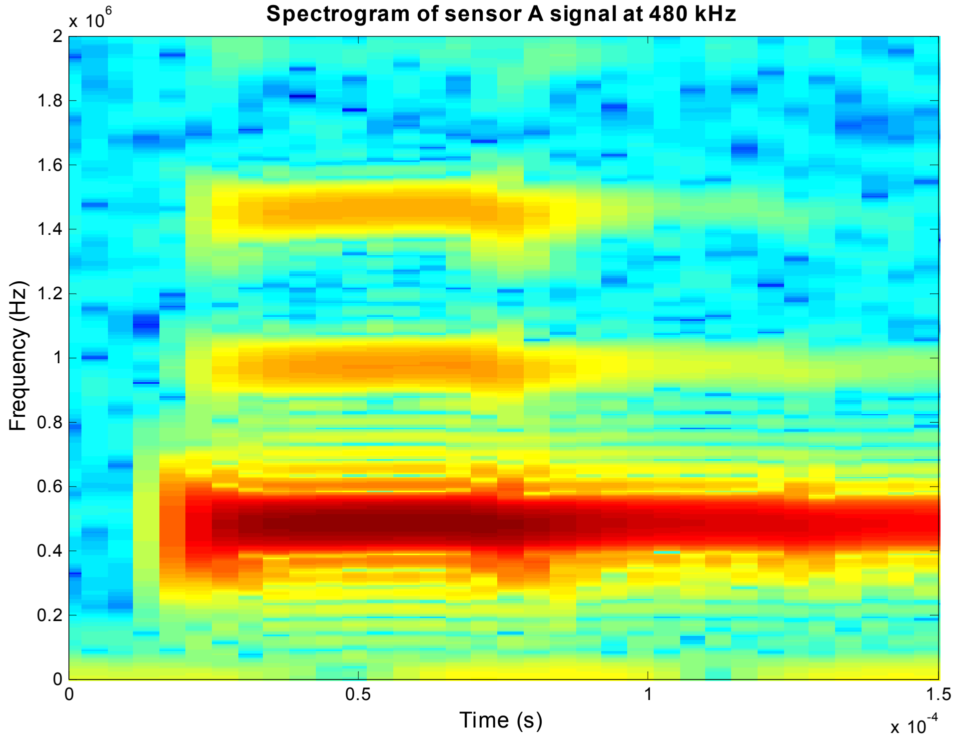

Figure 39: AE sensor spectrogram at 480 kHz

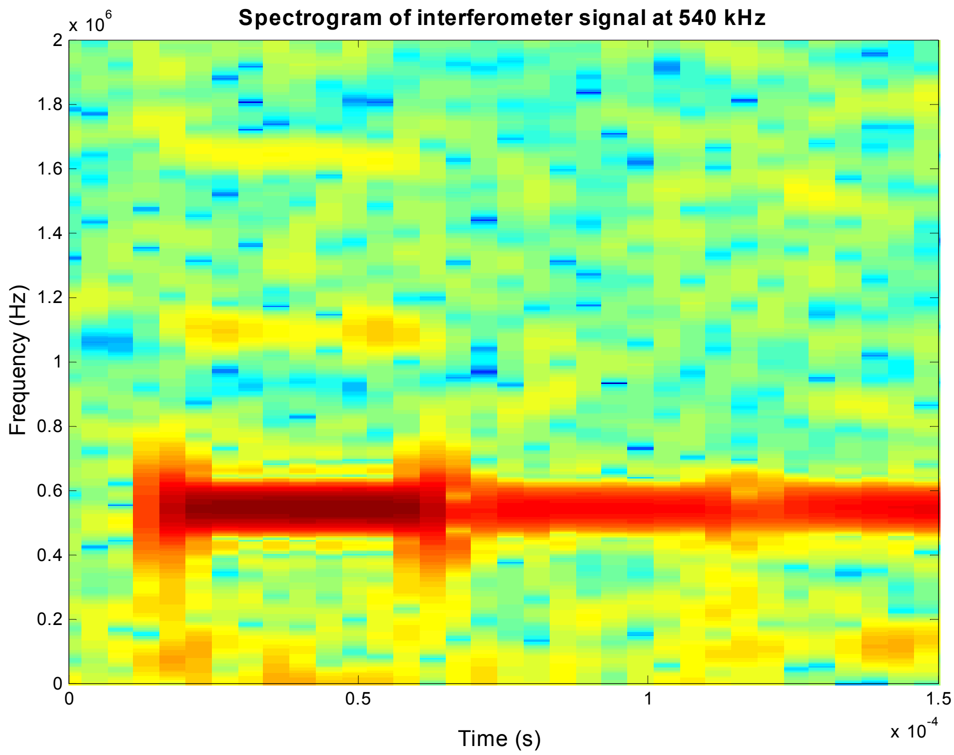

Figure 40: Interferometer spectrogram at 540 kHz

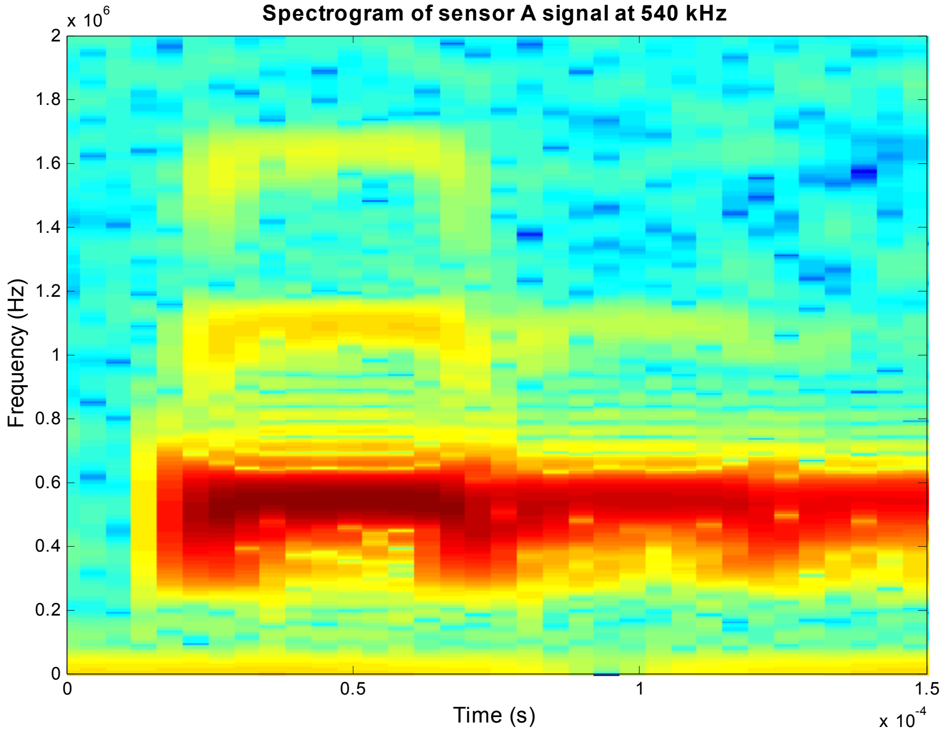

Figure 41: AE sensor spectrogram at 540 kHz

4.6 PHOTOMETRIC CONSULTANTS INTERFEROMETER AND CONICAL TRANSDUCER

The Photometric Consultants' interferometer was delivered at the end of the project described in this report and a limited set of test measurements was carried out to ensure that it was fit for purpose and met the specification for sensitivity and noise performance. The interferometer performed as expected with a noise equivalent displacement of the order of 3 pm. Some test measurements were carried out with a conical source transducer borrowed from Brunel University and an example of what can be achieved with the interferometer is shown in figure 42. A single cycle at 480 kHz was used to drive the conical transducer and the interferometer waveform was averaged 1000 times. A 50 kHz high pass filter was employed to remove low frequency components from the interferometer signal.

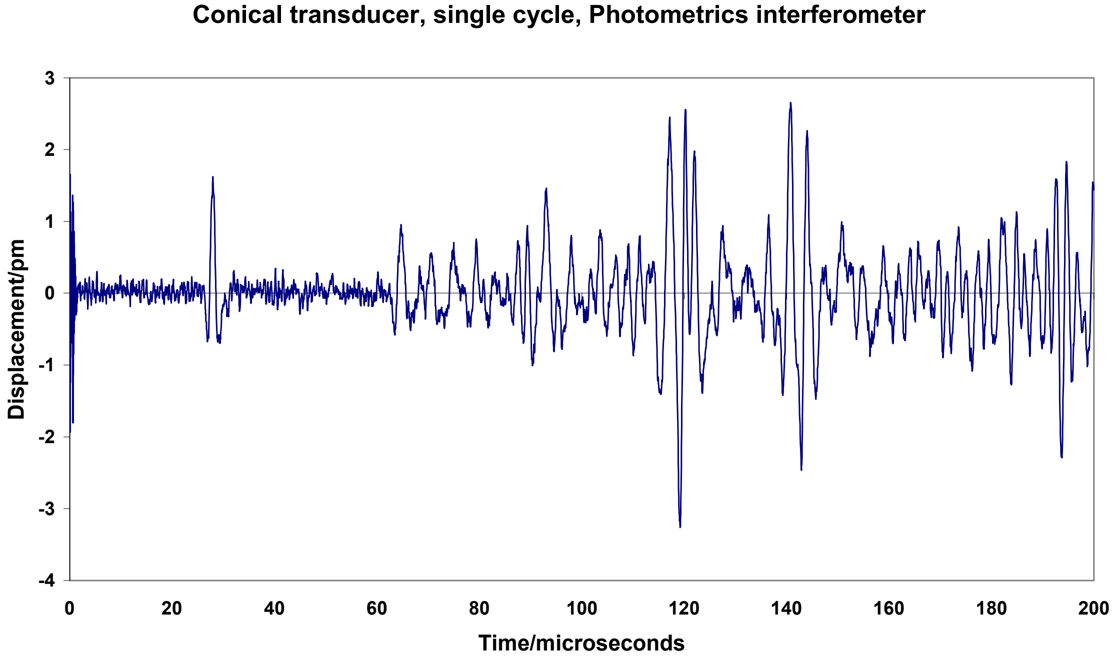

Figure 42: Photometrics interferometer response to single cycle 480 kHz wave form generated with conical transducer

Note the many echoes and reflections which arrive after the first reflection of the direct signal. The conical source, having a smaller contact area, is far less directional than the Panametrics transducer used for the results reported earlier in this chapter, so that the sound waves penetrate a larger volume of the block, including edge regions. Thus the trace shows the combined effects of longitudinal, shear and surface wave propagation, reflection and mode conversion in the block. The signal which appears at the start of the trace is an electrical artefact, arising from electrical pick-up of the trigger pulse by the high-pass filter. The noise performance of the interferometer can be judged by inspecting the trace in the region of the direct pulse. Here, averaging 1000 times, which would be expected to give a signal-to-noise ratio improvement of 32, has produced an apparent noise level of the order of 0.1 pm r.m.s. Further improvement in interferometer performance will require the elimination of specific interfering frequencies rather than a general reduction in noise levels. This is demonstrated in the frequency spectrum shown in figure 43. A 1000 point rectangular window was centred on the single-cycle direct pulse and the Fourier transform of this windowed pulse was calculated. Note both the relatively broad bandwidth of the pulse and the interference peak at approximately 1.3 MHz. The source of this has yet to be identified.

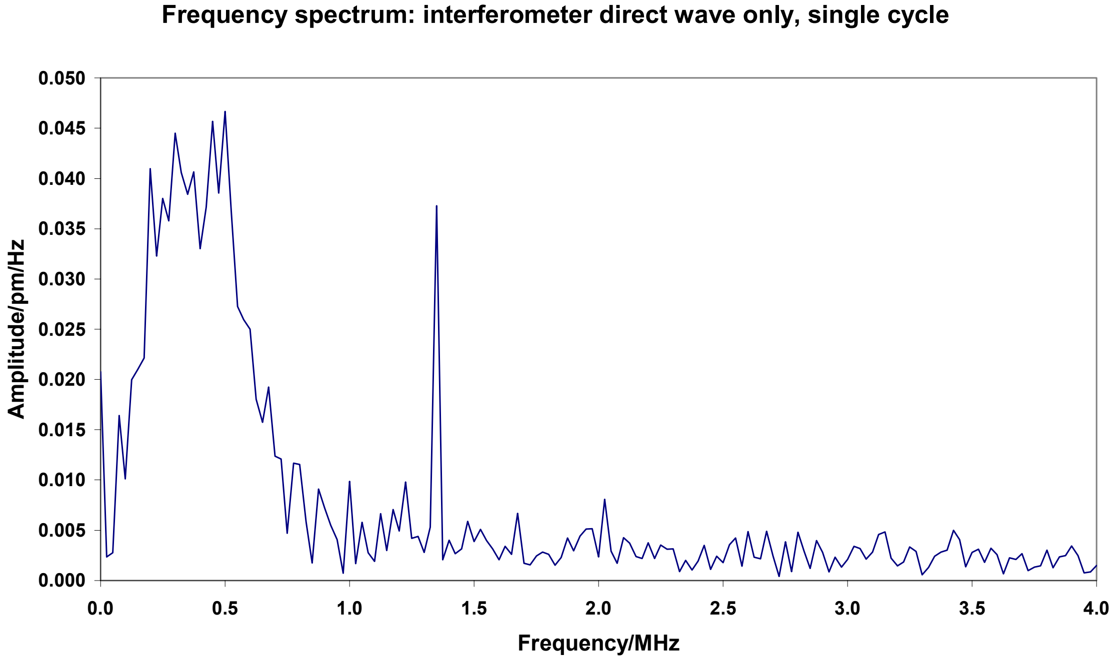

Figure 43: Frequency spectrum of single-cycle 480 kHz pulse generated by conical transducer

4.7 REVIEWING THE CALIBRATION RESULTS

The work presented in this chapter leads to three main conclusions. Firstly, given the relatively noisy nature of the interferometer signals and that the interferometer is in general less sensitive than the AE sensors undergoing calibration, broad band measurement techniques using short pulses appear not to be appropriate for calibration of highly-resonant, relatively narrow band AE sensors. Tone burst methods appear preferable.

The second conclusion relates to the size of the glass test block. The limited time window before the first reflections arrive and the fact that the AE sensors to be calibrated are highly resonant, mean that it is almost always impossible to achieve a steady state before the arrival of echoes and reflections. It is this limitation which gives rise to the variability associated with choice of signal processing and windowing methods. A larger block and therefore a longer time window uncorrupted by reflections would lead to reduced sensitivity of the calibration results to the choice of window length and position.

The third important observation relates to the variability which was observed when re-coupling transducers to the aluminium layer on the glass block's surface. To overcome this problem, two approaches are possible. One is to attempt to apply consistent force to transducers located on the aluminium layer, at the risk of damaging the layer, so that frequent replacement of the layer would be required. The second is to calibrate a limited number of reference transducers, such as conical devices used as receivers, in this configuration and then to use these as secondary standards to calibrate AE sensors by comparison with the conical receiver when both are coupled directly to a glass surface.

5 CONCLUSIONS

5.1 INTRODUCTION

In spite of a limited time scale and limited financial resources, this project has led to the successful development of a methodology and facility for acoustic emission sensor calibration. It has been shown that sensor calibration can be achieved, at least in compressional wave mode, by through-transmission using a well-characterised glass test block. A new laser interferometer of high sensitivity and excellent noise performance has been acquired and it has been demonstrated that laser interferometry provides an effective method of making non-contact measurements of surface displacement for calibration purposes.

The calibration method chosen for the work reported here has relied on tone bursts of relatively long duration. However, it has been shown that given the limited size of the glass test block, and the resonant nature of the AE sensors available for calibration, this method can be sensitive to the signal processing methods chosen for analysing the calibration data. To allow calibration of resonant sensors at lower frequencies than have been achieved in the work reported here would require a larger test block, if measurement uncertainties are not to become unacceptably large. Calibration of wide bandwidth sensors is likely to prove much less problematic.

The report has also reviewed existing international standards in the field of acoustic emission and describes calibration methodologies adopted by NIST and by other organisations with an interest in acoustic emission sensor characterisation. In addition, we have provided advice and guidance on calibration and testing methodologies for users of acoustic emission sensors.

5.2 TOWARDS TRACEABLE CALIBRATIONS: THE FUTURE

This project has shown a suitable specific methodology for calibration of acoustic emission transducers. Many items have been identified for further work, and the method itself requires further development and improvement prior to launch as a commercial service, including an extensive review of the associated uncertainties of measurement.

More generally, in the search for truly traceable AE measurements, rather than just calibration of the sensor, there are many avenues to be explored. Funding is available for starting this work under the DTI's current National Measurement System Acoustical Metrology Programme, but there are opportunities for industrial companies and SMEs to collaborate with NPL in this area. In particular later in the programme, NPL will be seeking organisations willing to make trial measurements in-situ, using NPL calibrated transfer standards.

One particular area where NPL will bring its expertise to bear is mathematical modelling. This will include modelling of wave propagation in acoustic emission test block materials, initially using simple blocks to gain further understanding of the physics of the detail of the wave propagation.

Further development work may also be required on the conical transducer. As has been pointed out, the brass shim could be replaced with a polyurethane tip, with the aim of reducing any coupling variability due to the shim itself. In addition the glass block surface is of good quality and movement of the transducer would be limited once in place.

Finite element modelling of conical piezoelectric elements will also have a rôle to play, in optimising the geometry of the cone and investigating wave propagation in the test block in the region close to the transducer, and in particular the interaction of the transducer with the test block.

Finally, we are hopeful that the introduction of acoustic techniques new to acoustic emission, such as those based on time reversal of acoustic signals, may provide a possible route to the quicker identification and sizing of cracks, and also allow the output of acoustic emission sensors to be related directly to the magnitude of source events which give rise to the detected signal.

6 ACKNOWLEDGEMENTS

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