NPL REPORT CMAM 79

REPORT

Summary of NDT/NDE-Related Research, Development and Facilities at the UK National Physical Laboratory

Compiled and Edited by

R C Preston

April 2002

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Centre for Mechanical and Acoustical Metrology, NPL

ABSTRACT
This report summarises the scientific and technical activities related to Non-Destructive Testing (NDT) and Non-Destructive Evaluation (NDE) currently being undertaken in the seven Scientific Centres at the UK National Physical Laboratory. The report consists mainly of a compilation of short descriptions of the technical topics and the main contact person(s) involved. Additional information concerning individual contact details can be found on NPL's web pages at http://www.npl.co.uk.

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Telephone, facsimile and E-mail addresses of NPL staff mentioned in this report can be found on NPL's web pages http://www.npl.co.uk/npl/search/staff.html.

Approved of behalf of the Managing Director, National Physical Laboratory by
Dr. G. R. Torr, Head of the Centre for Mechanical and Acoustical Metrology.

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1 INTRODUCTION

Non-destructive testing (NDT) and non-destructive evaluation (NDE) are terms used to cover a very broad range of techniques which are generally aimed at the identification, location and sizing of defects in materials and structures. Examples of traditional NDT/NDE techniques are the identification of defects in industrial components at the supply stage and the monitoring of crack growth in structural elements in a whole range of industrial systems. Sometimes the techniques are not so much looking for defects but may be investigating the quality of the product. NDT/NDE techniques are therefore found in one form or another in virtually all industries. Even in the office environment, techniques such as looking for watermarks by holding the paper up the light can be considered as an NDT/NDE technique. As well as covering more traditional NDT/NDE techniques, the scope of this report has been deliberately broadened to include physical measurement techniques that enable defects to be detected in samples. Hence, many of the entries are not strictly NDT/NDE techniques but may have potential for development into such.

Distributed over the seven NPL Scientific Centres there are many research and development projects directly related to NDE/NDT, or which have relevance to NDE/NDT. The purpose of this report is to provide a simple summary of the main elements of the various technical areas. To this end, Section 2 provides a Centre-by-Centre short-form summary and outline of the technical work related to NDT/NDE and identifies the main contact persons. Overall, the technical areas where NPL has expertise, capabilities and facilities include:

- AC conductivity
- Acoustic emission
- Acoustic and ultrasonic transducer modelling
- Dielectric measurements
- Dimensional measurement
- Electronic speckle pattern interferometry
- Fibre optic strain
- Fibre optic techniques
- Fluorescence
- Fracture mechanics
- Impact excitation
- Internal temperature measurement
- Laser-acoustic thin film analyser
- Low relative magnetic permeability for NDE
- Magnetic and electrical NDE methods
- Modelling and computational techniques
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- Nuclear spectrometry
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- Stress and structure - piezospectroscopy
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- Thermal imaging and analysis
- Ultrasonics
- Ultrasonic C-scanning
- Ultrasonic transducer characterisation
- Ultrasonic properties of materials
- Video extensometry
- X-ray radiography and inspection

In a few of the technical areas, a little more detail is given in Section 3 which serves to show the range and quality of NPL's work. Finally, as a demonstration of cross-Centre involvement, Section 4 gives a tabular summary of the cross-Centre activities in the different technical areas. It is seen that in over 40% of the topics, more than two Centres are actively involved.

The NPL Scientific Centres are:
- Centre for Basic, Thermal and Length Metrology - CBTLM
- Centre for Electromagnetic and Time Metrology - CETM
- Centre for Ionising Radiation Metrology - CIRM
- Centre for Mathematics and Scientific Computing - CMSC
- Centre for Mechanical and Acoustical Metrology - CMAM
- Centre for Optical an Analytical Metrology – COAM
- Materials Centre - MATC

Figure 1 shows that each Centre contributes to NPL's overall capability in NDT/NDE.

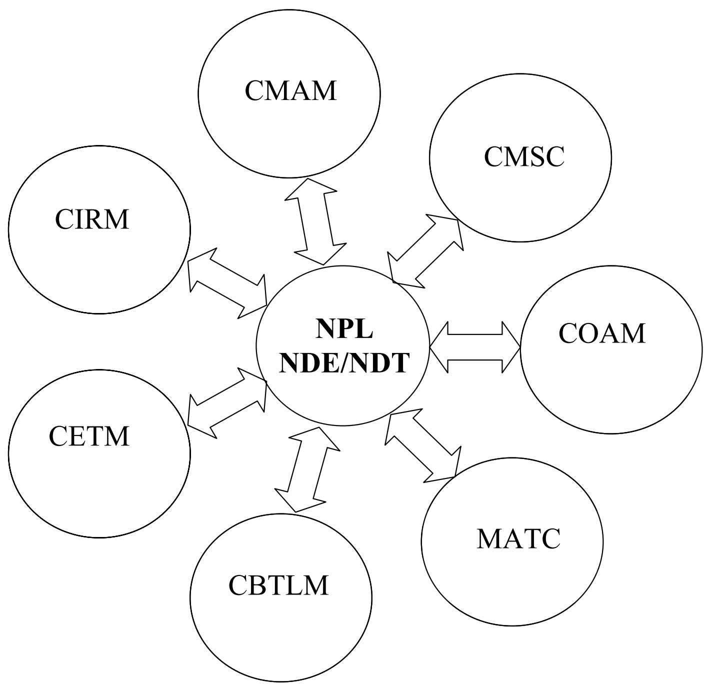


Figure 1: Each NPL Centre contributes to NPL's capability in Non-Destructive Testing and Evaluation

2 NDT/NDE Activities in NPL Centres

2.1 Materials Centre (MATC)

2.1.1 Acoustic emission

MATC is working with acoustic emission (AE) to detect oxide cracking on industrial components and for monitoring the onset and progress of damage in fibre-reinforced polymer composites. For composites, AE is being used to assess the reliability of life prediction models being developed at NPL. This evaluation has included correlation studies with optical measurements. There is some work with electrochemical methods on crack detection. The Centre has a number of personnel with experience in the use and interpretation of AE for a wide range of applications.

Contacts:
Stuart Saunders, MATC
Alan Turnbull, MATC
Graham Sims, MATC

2.1.2 Acoustic emission (AE) system

The Mistras AE system 2001 (Physical Acoustics Corporation) is being routinely applied to a wide range of applications for monitoring the onset and propagation of damage in multi-layered systems (including oxide layers on metal substrates, coatings and composite laminates). AE can be used to monitor real-time events of structures under stress, which includes simple coupon specimens and complex multi-component structures. The Mistras system used in MATC is a two-channel software driven system. It can record 20,000 hits/sec for a single channel. The hit data information recorded by the system includes, time of hit, energy, amplitude, duration, count, rise time, etc. These parameters can be plotted against real-time, load or displacement. The system can also record the transient waveform of the AE source. The AE sensors can operate over the temperature range – 45 °C to 80 °C.

Contact:
Jim Banks, MATC

2.1.3 Electronic speckle pattern interferometry (ESPI)

ESPI offers a very accurate method for measuring thermal expansion coefficients and elastic properties of isotropic and orthotropic (i.e. composite) materials. The technique can be applied to relatively large specimen dimensions of 100 mm x 100 mm (or greater) and can be used with complex specimen geometries. It is a full field non-contact (optical) measurement technique that can be used to measure displacement (strain) to an accuracy of 1 to 2 μm in the orthogonal directions (i.e. 3-D) under quasi-static load. Sample preparation is straightforward and requires minimum handling. Images are recorded using a CCD video camera and evaluation software is used to transform the fringe information into deformation and strain data. The system is used for detection and modelling of sub-surface damage in multi-layered structures, validation of FEA analysis for design purposes and for assessing mechanical test methods for polymers and composite materials. It is a reliable alternative to strain gauges and contact extensometers for measuring displacement and strain, and can be used to determine changes in material stiffness resulting from sub-surface micro-damage.

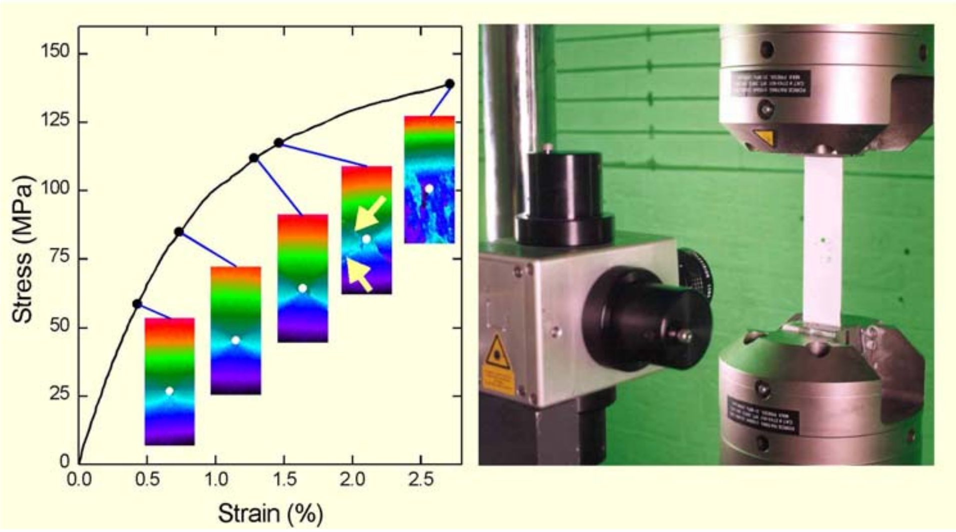


Figure 2: Open-hole tension test of composite laminate.

Contacts:
David Mendels, MATC
Graham Sims, MATC

2.1.4 Electronic speckle pattern interferometer system

The ESPI facility (Ettemeyer AG, Germany) has a sensitivity of approximately 2 µm in-plane and 0.415 µm out-of-plane. Strain resolution has been enhanced through the use of a set of Pentax Comiscar® lenses inserted in front of a CCD camera (752 x 582 pixel) used to record speckle pattern fringes. The system allows for real-time measurement of deformation and strain of simple and complex structures under quasi-static loads. The imaging field goes from 2 mm x 2 mm to 100 mm x 100 mm, which is expandable to areas as large as 1 m x 1 m with the use of suitable lenses.

Contact:
David Mendels, MATC

2.1.5 Fibre optic strain monitor

NPL has developed a very sensitive fibre optic monitor for strain measurements. The portable system can be used with fibre optic sensors attached to the surface or embedded in a structure, thus allowing for continuous or periodic monitoring. The equipment potentially is suitable for monitoring structural integrity of civil infrastructure, such as road and railway bridges, to assist maintenance and extend the operational life of these structures. The equipment has been used to monitor strain continuously in composite laminates under thermo-mechanical loads. The system has an operating range of 25 to 100°C with a temperature sensitivity of 0.005°C. The strain resolution is 0.05 microstrain and a strain range of ± 3%. It can be used to validate strain gauge data and FEA. Potential applications include automotive parts, adhesive joints, cure monitoring and deterioration in material and structural properties.

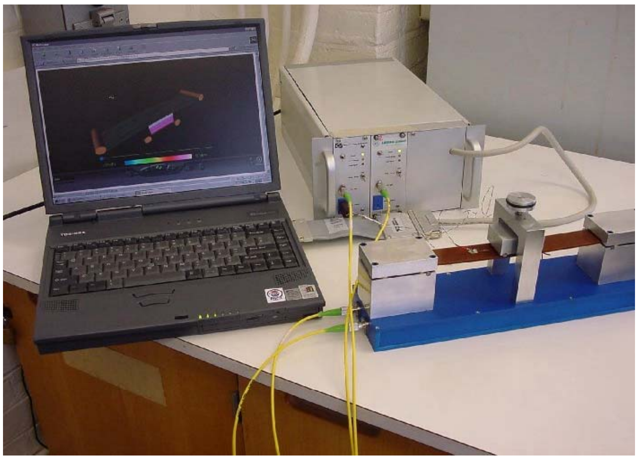


Figure 3: Fibre optic monitor for strain measurements

Contact:
Markys Cain, MATC

2.1.6 Fracture mechanics

MATC has significant expertise in fracture mechanics which is an essential part of assessing the significance of crack-like defects that are found in any non-destructive test. The NPL speciality is the analysis of composite defects such as ply cracking and delamination. Work is now starting on modelling of delaminations and defects in coatings. The work involves materials experts and experts in data analysis and mathematical modelling. While the planned work is not directed towards NDE, it could have spin-offs in that direction.

Contacts:
Neil McCartney, MATC
Louise Wright, CMSC

2.1.7 Functional materials

The Functional Materials Group within MATC has investigated various scientific issues regarding the NDT/condition monitoring of functional and smart materials and structures. Examples have included the use of acoustic emission analysis from electrically excited piezoelectric ceramic materials and specifically the study of the effect of mechanical fatigue on the acoustic emission. Another technique investigated was the use of thermal imaging to identify damage to multilayer actuators following mechanical damage to the device.

The Functional Materials Group has also played a significant part in an INTErSECT Faraday Partnership Flagship Research Project (1998-2002) - Acoustic Emission Traceable Sensing and Signature Diagnostics (AESAD). Primary objectives are: to develop a robust scheme for traceable calibration of AE transducers; to develop a reliable means for signature analysis; to demonstrate the use of a novel methodology for traceable calibration of AE transducers in-situ in several diverse industrial applications; and to produce a set of guidelines on AE monitoring for diagnostic and control purposes (see also 2.4.1).

Contact:
Markys Cain, MATC

2.1.8 Laser-acoustics thin film analyser

The laser-acoustic thin film analyser LAwave3.1 (Fraunhofer Institute for Material and Beam Technology) can be used for determining the Young's modulus of films (e.g. oxide layers on metallic substrates) with thickness in excess of 10 nanometres up to a 2 to 3 μm, although it can provide useful information for coatings that are almost 1 mm thick. The Young's modulus of the substrate is also provided. The technique can be used to determine the effective elastic constants of multi-layer films consisting of two components, and is suitable for use with metals, ceramic and semi-conductor (e.g. silicon and gallium arsenide wafers) materials, and for characterising the elastic anisotropy of bulk material. Laser-acoustics offers quick and reliable measurements, and can be used to assess surface treatments of metals.

Contact:
Giles Aldrich-Smith, MATC

2.1.9 Properties of hard materials

MATC has considerable expertise in the use of magnetic and electrical NDE methods for characterising the structure of extremely fine structured materials. Recent work with industry has provided an understanding of the effects of processing variables on structure and it is expected that this work will shortly be extended to nanostructured materials.

Elastic properties of homogeneous materials can be measured non-destructively using the impact excitation method on both bars and discs. This system produces data the accuracy of which is limited primarily by the ability to 'ring' and the dimensional perfection. It can also be used to elevated temperatures. This is a quick and effective method, but has limited capability if the elasticity is anisotropic, in which case an ultrasonic velocity method is needed (also available in MATC). The method can also be used to monitor changes in components with service, and has been used extensively for the performance of silicon carbide dust filter elements for power and incinerator plant.

Contacts:
Bryan Roebuck, MATC
Roger Morrell, MATC
Mark Gee, MATC

2.1.10 Scanning acoustic microscopy

MATC has an UHR-2000 Ultra High Resolution Sonix Scanning Acoustic Microscope (SAM) for use in a wide range of applications (including biomaterials and electronics) to produce internal images of materials and components. The system is able to image features down to about 3-5 μm in diameter. For 2-D features, such as disbonds and delaminations, these can be imaged when their "through thickness" dimension is less than 1 μm. This makes acoustic microscopy ideal for detecting such features, where alternative methods such as X-ray inspection are generally not effective. The SAM can be used for investigating defects and voids in adhesive joints, monitoring progress of underfill in electronic assembles, inclusions in steel and fatigue damage in composite laminates. It is intended to use the equipment to measure the properties of arterial walls and the surface of teeth. Special software can be used to generate a tomographic scan of a sample. This means that all of the internal interfaces of the sample can be displayed in a single scan.

Figure 4: Scanning acoustic microscope

Contact:
Paul Tomlins, MATC

2.1.11 Stress and structure - piezospectroscopy

NPL has the capability to make stress measurements using optical spectroscopic techniques. This approach is known by the generic term of piezospectroscopy. The main techniques employed are fluorescence and Raman measurements, and they can be applied to a range of materials and components where the frequencies (and shape) of the fluorescence or Raman features are stress dependent. Measurements can be obtained on the macroscopic (mm) or microscopic (μm) scale. The techniques also give information about the microscopic structure of the materials and, for example, can be used to discriminate between different phases of a material. This capability is the result of cross-Centre collaboration between MATC and COAM.

There is a current research project concerned with developing these techniques to predict reliably the lifetime of thermal barrier coatings (TBCs) and producing a prototype fluorescence NDE instrument for field testing on TBCs.

Contacts:
Stuart Saunders, MATC
Chris Chunnilall, COAM

2.1.12 Residual stress

As well as piezospectroscopy (see 2.1.11), MATC has expertise in measuring residual stress via X-ray diffraction and hole drilling - techniques that can be applied to a range of materials and components. The current research project has focused on assessing the accuracy and uncertainties associated with XRD and hole drilling in some detail, developing separate Good Practice Guides for the two techniques to provide UK industry with reliable test methods and as an input into the European standards activity. Through this work, NPL has developed excellent links with the key UK industrial and academic users.

Contact:
Jerry Lord, MATC

2.1.13 Thermal analysis
MATC has a Merlin InSb laboratory camera, which is a high-performance mid-wave infrared (MWIR) camera system. The system has excellent sensitivity over the 3.0 to 5.0 μm waveband, the standard bandpass for the camera. The passband of the laboratory system can be expanded by changing dewar windows and cold filters (1.0 to 5.0 μm). The camera operates at a fixed frame rate of 60 Hz. The unit can be used to continuously monitor changes in surface temperature to within 0.01°C with no limit on the surface temperature of the heat emitting body. It has an RS32C user interface to enable images to be down-loaded and analysed using a PC.

Contact:
Jim Banks, MATC

2.1.14 Ultrasonic C-scanning
MATC has extensive experience using ultrasonic C-scan techniques for inspecting fibre-reinforced plastic composites. Expertise has been developed at NPL in using these techniques to detect, measure and characterise a wide range of manufacturing and in-service defects in these materials. Reference panels with simulated defects have been produced and supplied to industry.

See also Section 3.1.

Contact:
Bill Broughton, MATC

2.1.15 Ultrasonic C-scan system
MATC has a Meccasonics ultrasonic C-scan facility (MIDAS software) suitable for inspection of flat and slightly curved composite panels. Inspection Modes include: (i) single through-transmission (immersion and water jet); (ii) double through-transmission; (iii) contact; and (iv) time-of-flight facility. The ultrasonic C-scan system is capable of detecting defects 2-3 mm in 50 mm thick prepreg and woven laminate panels with a working area of 500 mm x 500 mm. The attenuation resolution is approximately 0.1 dB.

Contact:
Bill Broughton, MATC

2.1.16 Video extensometry
MATC has video extensometry equipment for large 2-D strain field measurements. These systems enable simultaneous stiffness and Poisson's ratio measurements up to large strains with a strain resolution of approximately 10 microstrain. Multiple gauge-sections can be viewed enabling study of localised strain. Area of inspection is unlimited from the microscopic to large structures. As video extensometry is a non-contact technique, it can operate over any range of temperatures with no possibility of damage to the equipment or

to the specimen. A MINTRON CCD video camera is being used in conjunction with MESSPHYSIK windows based software for measuring large deformations in polymeric materials under tensile loading conditions. This device is also being used with bulk adhesives and adhesive joints for materials characterisation and modelling validation purposes.

Contacts:
Bruce Duncan, MATC
Steve Osgerby, MATC

2.1.17 X-ray radiograghy

Faxitron X-ray machine (Buehler Krautkramer) with 150 keV X-ray source for inspection of fibre-reinforced plastic panels. The system is capable of detecting micro-cracks (approx. 1-2 μm wide) in damaged panels. The equipment is being used to detect and characterise damage in composite structures resulting from monotonic, fatigue and impact loading. Further work is needed to generate standard operational procedures and to assess the capabilities of the kit for inspecting polymer matrix composites (PMCs). The system uses photographic film for recording information. The equipment complements the ultrasonic C-scan equipment.

Figure 5: Impact Damage of carbon/epoxy laminate.

Contact:
Mike Gower, MATC

2.2 Centre for Electromagnetic and Time Metrology (CETM)

2.2.1 AC Conductivity for NDT

CETM provide a range of conductivity standards for calibrating commercial conductivity instruments used in NDE applications. These instruments typically cover a conductivity range of 1.2 MS/m to 58 MS/m and usually operate at 60 kHz. The standards available from NPL are calibrated at the frequency of operation of the instruments. Other standards have a DC calibration and the question of material uniformity through the thickness arises. The conductivity traceability provided underpins areas such as crack detection.

Contact:

Michael Hall, CETM

2.2.2 Low Relative Magnetic Permeability for NDT

In many situations it is essential that the magnetic behaviour of materials is not significant. The parameter used to determine this is the relative magnetic permeability. Commercial instruments exist for measuring the relative magnetic permeability of materials and these need traceable calibration. NPL has developed a range of permeability standards to provide this traceability and can offer consultancy on important issues such as the effect of the geometry of the test specimen being measured and the importance of the applied magnetic field strength used for the measurements.

Contact:
Michael Hall, CETM

2.2.3 Terahertz imaging

Frequencies available from terahertz systems typically range from 0.1 - 2 THz and can be used in an X-ray imaging type configuration for medical or NDT testing. This is a new technical area and systems demonstrated outside NPL are often compared with medical CT scanners, but with the added benefit of identifying material types through differential absorption of the THz radiation by different materials.

At NPL the generation and detection of THz radiation has been demonstrated using short laser pulses and in-house developed THz semiconductor devices. Power levels from the NPL demo system were in the micro-watts region and imaging with the system was limited. This demonstration project was funded internally. It is expected that new projects will be undertaken in this area.

NDT Application - THz radiation is readily absorbed by water and this is its main use in medical imaging. THz radiation cannot penetrate metallic objects, but could perhaps be used for identifying metal within other ceramic/GRP materials where there would be a good contrast.

Contact:
Richard Dudley, CETM

2.2.4 Dielectric measurements

Dielectric measurement is not traditionally a major player in the NDT stakes but a few techniques are relevant.

Reflectometric (e.g. coaxial) probes can be used to measure the properties of certain types of dielectrics from their surfaces, but very good contact is essential across the whole face of the probe. This requirement usually excludes hard surfaces and restricts one to malleable surfaces (e.g. human skin, certain foams, plastics, etc, also good for liquids). The technique is best suited to lossy materials.

Radiated wave transmission, reflection or resonant techniques are actually used in materials processing, e.g. measuring moisture-content of a role of paper sheet in real time by feeding it through a microwave measurement cell. These techniques are good for thin materials. A variation might be measuring absorption in dielectric rods/tubes fed down the axis of a resonant cavity from the cavity Q-factor. Resonant methods are best for low loss, transmission for high loss. The method can also be used in other areas such as for quantifying rainfall.

More sophisticated radiated signal techniques can also be considered. For example: radar, arguably, is a form of dielectric NDT and can also be used for measuring rainfall, etc. Going a step further, certain types of impedance, capacitance and dielectric tomography might be used for NDT purposes.

See also Section 3.3.

Contact:
Bob Clarke, CETM

2.3 Centre for Ionising Radiation Metrology (CIRM)

2.3.1 X-ray facilities

CIRM has extensive facilities for generating X-ray and gamma-ray fields, many of which could be used for radiographic examination. Facilities include 50kV, 150kV, 300kV and 420kV X-ray exposure suites, Cs-137 and Co-60 gamma ray irradiation facilities and an electron accelerator capable of generating X-rays (bremsstrahlung) from electron beams in the energy range 5 – 20 MeV. To date, NPL's direct experience has been in radiographing of works of art, but the facilities can be used for a variety of nuclear/radiation-based NDE/NDT.

Contact:
Alan DuSautoy, CIRM

2.3.2 Nuclear spectrometry

CIRM has an extensive range of facilities and experience in the use of gamma-ray and alpha-particle spectrometry and related non-destructive nuclear analysis techniques. CIRM also carries out analysis of industrial, medical and environmental samples and has run intercomparison exercises for people who are involved in such analyses.

Contact:
Simon Jerome

2.3.3 Assay of nuclear materials

CIRM is currently leading a project on nuclear non-destructive assay measurements for the nuclear fuel cycle. This has involved the preparation of a Good Practice Guide for radiometric non-destructive analysis measurements. This is intended to assist the regulators and licensees in agreeing what is "reasonably practicable" and has been prepared with specialist input from experts across all aspects of the non-destructive assay community in the UK.

Contact:
Vic Lewis, CIRM

2.3.4 Neutron measurements

CIRM is also involved on various aspects of neutron measurements. Although not specifically NDE projects, relevant topics are:

- Neutrons are used for radiography to show up hydrogenous materials, e.g. oil in pipes, in contrast to the high-Z materials seen with conventional X-rays. The work is done with thermal neutrons, so the main requirement is an intense source of thermal neutrons. NPL's expertise is in measurement of neutron fluences which could be relevant to any new work in this area.
- NPL also has expertise in running neutron transport Monte Carlo codes which can be used in designing and optimising systems.

Contact:
David Thomas

2.4 Centre for Mechanical and Acoustical Metrology (CMAM)

2.4.1 Acoustic emission (AE)

CMAM is undertaking studies of methods of calibrating acoustic emission transducers in a new research and development programme. These involve:

- Development of broadband reference sources;
- Establishment of reference calibration test blocks;
- Interferometric measurement of AE signals;
- Investigation of the possible use of time-reversal techniques for enhanced acoustic emission.

CMAM is also involved in the acoustic emission INTErSECT Faraday Flagship project, as mentioned in Section 2.1.7. Concepts of calibration based on energy are being explored as are methods of using secondary standard sources.

See also Section 3.2.

Contact:
Sue Dowson, CMAM

2.4.2 Ultrasonic properties of materials

CMAM has established special facilities for the determination of the speed of sound, attenuation and in principle dispersion of materials used for ultrasonic applications in the frequency range 1 MHz to 20 MHz, depending on the type of sample.

Contact:
Bajram Zeqiri, CMAM

2.4.3 Ultrasonic transducer characterisation

CMAM has unique capability to map the spatial distribution of ultrasonic fields in water over the frequency range 1 MHz to 100 MHz. The techniques utilise a wide range of membrane and needle-probe hydrophones and special measurement facilities. Also a unique system utilising a multi-element hydrophone and data acquisition and control has been developed for the rapid evaluation of ultrasonic beams from real time scanners such as linear and phased arrays.

Contact:
Bajram Zeqiri, CMAM

2.4.4 High frequency optical interferometry

CMAM has developed and maintains a special interferometer with a bandwidth up to 100 MHz which is used as a primary standard for the calibration of ultrasonic hydrophones. It can also be used for the interrogation of surface displacements.

Contact:
Bajram Zeqiri, CMAM

2.5 Centre for Basic, Thermal and Length Metrology (CBTLM)

2.5.1 Internal temperature measurement

Internal measurement of temperature has a wide range of applications in industry as a non-destructive diagnostic tool. CBTLM will be undertaking work in this area over the next three years. The development of these technologies for internal temperature measurement is likely to be of increasing value in industry.

Contacts:
Gordon Edwards, CBTLM
Andrew Levick, CBTLM

2.5.2 Photothermal (PT) technologies

CBTLM is developing photothermal technologies for the measurement of temperature and thermophysical parameters. PT methods are already important and developed in certain areas of NDT although there seems to be relatively little work in the UK. The PT skills in CBTLM will be expanded over the next few years which will enhance the work relevant to NDT.

Contacts:
Gordon Edwards, CBTLM
Andrew Levick, CBTLM

2.5.3 Fibre optic techniques

Collaborative work in CBTLM is being pursued for the use of a fibre-optic technique for measuring molten metal temperatures and in the use of fine optical fibres to monitor/measure parameters during materials processing such as rolling and pressing.

Contacts:
Gordon Edwards, CBTLM
Andrew Levick, CBTLM

2.5.4 Dimensional measurement

CBTLM has extensive dimensional metrology capability. Dimensional metrology offers the possibility of using existing expertise for measuring deformations mainly DC or low frequency. This could be due to the effects of gravitational sag in the case of large telescopes, pressure, delamination, etc. One application area of interest to CBTLM is where there is a requirement for measuring accurately the relative disposition of components inside an outer container with only minimal access.

Contact:
Graham Peggs, CBTLM

2.6 Centre for Mathematics and Scientific Computing (CMSC)

2.6.1 Signal processing for acoustic emission

Signal analysis is crucial to understanding the signals from acoustic emission systems. CMSC is involved with signature analysis and diagnostics for acoustic emissions (INTErSECT project AESAD), involving skills in signal processing, wavelets and classification theory.

Contact:
Gavin Kelly, CMSC

2.6.2 Modelling and computational techniques

Many NDT/NTE applications involve difficult modelling and computational problems. The EPSRC's Computational Engineering Mathematics Programme has identified ultrasonic modelling for NDT as an emerging technology and noted the synergy with electromagnetics as both involve the problem of wave propagation in complex media. It has also indicated the need to model the stochastic (i.e. random) component of these problems. CMSC has some expertise in this area.

Contacts:
Alistair Forbes, CMSC
Louise Wright, CMSC
Mark Dainton, CMSC

2.6.3 Modelling transducers

NPL is also involved in modelling transducer behaviour in ultrasonics and underwater acoustics using various techniques including finite elements.

Contacts:
Peter Harris, CMSC
Stephen Robinson, CMAM
Trevor Esward, CMAM
Pierre Gélat, CMAM

2.7 Centre for Optical and Analytical Metrology (COAM)

2.7.1 Non-Destructive-Testing UV

Routine screening of critical metal structures such as aircraft for fine cracks due to stress or metal fatigue are often carried using UV radiation. A dye which fluoresces under UV radiation is sprayed on to the metal and absorbed into any cracks. The surface is then washed before illuminating with intense UV radiation. The intensity and spectral content of the UV is governed by regulation. NPL provides traceability to the UV meters used to determine this irradiance level.

Contact:
Nigel Fox, COEM

2.7.2 Thermal Imaging in NDT

The presence of a sub-surface defect or void in a component will alter the heat flow through that component. This generates temperature variations on the surface which can be detected by a thermal imager. Modern thermal imaging systems based on focal plane arrays are capable of 20 mK temperature resolution and with the appropriate imaging system have spatial resolution below 100 µm. In some instances, the body under test must be heated or cooled, but the emergence of a body from an oven into an ambient temperature environment is usually sufficient.

The main attraction offered by thermal imaging over alternative NDT methods is that it is a non-contact method. This coupled with the very fast frame rates available by modern thermal imaging systems makes thermal imaging inherently fast and this has generated numerous applications in the inspection of fast moving objects leaving a production line. Finally, the method produces a two dimensional image which is far easier to interpret. Thermal imaging is being used in the non-destructive testing of honeycomb structures, adhesive joints, de-bonding of paint films etc.

Thermal imaging can also be used to detect surface defects such as the non-uniform deposition of coatings, relying on the difference in the emissivities of the coating and the substrate for detection. NPL has expertise in the interpretation and performance of such tests

Contact:
Nigel Fox , COAM

3 Examples of specific technical activities related to NDT/NDE

This Section gives a few examples of NPL work directly related to NDT/NDE. The examples range from C-scan standardisation, where NPL has established a significant capability, to totally new areas such as the calibration of acoustic emission transducers. Dielectric measurements are also highlighted as an example of a technique that offers considerable future potential. Finally, work done on functional materials utilising thermal and acoustic emission techniques demonstrates the multi-disciplinary work at NPL. These topics covered are intended solely as examples of NPL's work in the NDT/NDE area.

3.1 Ultrasonic C-scan development and standardisation

Through partnership with industry, MATC has developed expertise in using ultrasonic C-scan techniques to detect, measure and characterise a wide range of manufacturing and in-service defects in fibre-reinforced plastic composites. A programme, sponsored by the DTI under the Commercial Aircraft Research and Development (CARAD) programme, which was led by NPL in collaboration QinetiQ (formerly DERA) resulted in three draft procedures covering:

- Operational procedures for ultrasonic C-scan equipment
- Ultrasonic transducer calibration procedure
- Procedure for the preparation of reference panels with simulated defects

The draft procedures have been submitted to CEN for consideration as new work items for standardisation.

MATC has the expertise and facilities to produce calibration/reference panels with simulated production defects (e.g. inclusions, delaminations, heat damage, chemical contamination and resin rich regions). These panels can be used to establish, prior to inspection, that the ultrasonic C-scan equipment/instrumentation is functioning correctly and that the sensitivity and resolution is appropriately adjusted. The calibration/reference panels are suitable for inspection of autoclave produced carbon and glass fibre-reinforced prepreg laminates up to 50 mm thick. The underpinning research was undertaken within the CARAD project and AMCAPSII, a project led by Airbus.

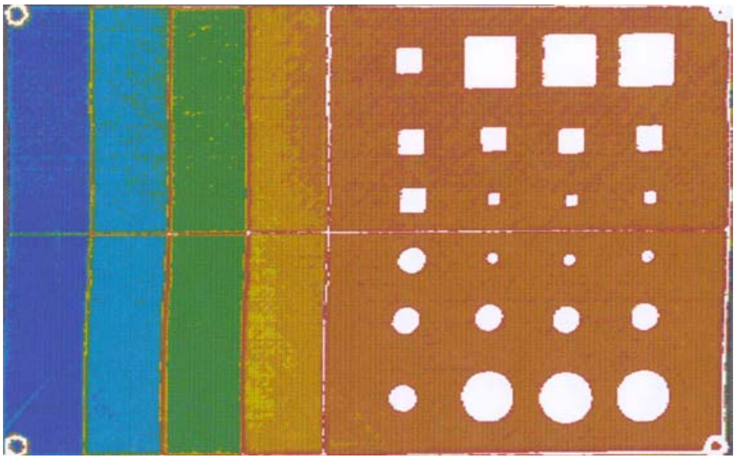


Figure 6: Ultrasonic C-scan image of stepped carbon/epoxy laminate with inserted defects

Contact:
Bill Broughton, MATC

3.2 Acoustic emission

A relatively new scientific topic at NPL is CMAM's work on acoustic emission that aims to establish traceable calibrations for AE transducers.

Acoustic emission (AE) refers to acoustic (ultrasonic) energy, emitted from a process or material, which can provide further information about that process/material. In particular, it is used to detect the development of cracks in structures and wear in rotating machinery. Application of AE techniques 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 there has been more interest in the use of AE as an in-service condition monitor and as an on-line process monitoring technique. Examples of use cover a wide spectrum, from monitoring of large pressure vessels, storage tanks, and large structures such as bridges and aircraft structures, to studying toolwear and composition of chemical liquids.

There is no recognised method of calibrating acoustic emission transducers and no traceability, despite the fact that AE has been used for many years. With the development of greater computer processing capability providing the opportunity for more sophisticated methods of data analysis, AE systems are becoming more powerful and relevant to the industrial community. AE traceability is therefore of an increasing interest. The CMAM work builds on the current INTErSECT project on acoustic emission with emphasis on the development and establishment of reproducible sources, transfer standards and the calibration of industrial acoustic emission probes.

Work is taking place to establish a reference test facility, which will include well-characterised reference test blocks, see Figure 7, and secondary standard sources. Optical interferometric techniques will also be used to characterise the acoustic particle displacements and velocities. A glass reference block is being employed to enable a wider range of optical measurements to be made. Although the breaking of the lead of a fine lead pencil has been used widely as an AE source, it is intended to establish a repeating and reproducible AE source to enable greater accuracy to be achieved during the calibration of AE transducers. In combination with these mainly experimental activities, new work will look at modelling of the acoustic propagation in order to understand more fully the interaction of different wave modes (compressional, shear and surface waves) with the transducers under test.

Figure 7: AE transducers placed on an aluminium test block.

Finally, the technique of time-reversal may offer the opportunity of actively combining acoustic emission with ultrasonic non-destructive testing, thereby significantly enhancing the sensitivity of both location of defects and their characterisation. A study will be undertaken of the feasibility of using time-reversal techniques in acoustic emission.

Contact:
Sue Dowson, CMAM

3.3 Dielectrics

Dielectric measurements are well established in CETM and although they are not traditionally a major player in NDT, a few techniques are relevant and could increase in importance in the future.

Reflectometric (e.g. coaxial) probes can be used to measure the properties of certain types of dielectrics from their surfaces, but very good contact is essential across the whole face of the probe. This requirement usually excludes hard surfaces and restricts one to malleable surfaces, e.g. human skin, certain foams, plastics, etc, liquids. The technique is best suited to lossy materials and is commonly used in bio-medical studies on tissues and in measurements on lossy liquids. The coaxial probe in Figure 8 is fully calculable, i.e. the permittivity of the material it is in contact with can be computed analytically from the measured reflection coefficient. Other, 'non-calculable' probes are also used, they are usually cheaper to construct and are often more amenable for use in out of laboratory (e.g. production) conditions or at temperatures away from the ambient. Although such sensors are non-calculable they can be calibrated by use of a range of reference materials. In some applications full calculability is not required, the ability to detect deviations away from a specified permittivity is adequate. Reflectometers vary from Automatic Network Analysers (expensive but calculable) to simple resonant detection systems (cost-effective for fixed applications).

Figure 8: A 15-mm diameter Coaxial Dielectric Probe for dielectric measurements in the 100 MHz – 3 GHz frequency range. Such probes are best suited to NDT on malleable solids and liquids. The figure shows the coaxial open end of the probe, the aperture of which (i.e. the circle of the white PTFE dielectric between inner and outer conductor) has a diameter of 15 mm. The other end of the probe is connected to a reflectometer. Such probes can typically vary in aperture from 50 mm down to 2 mm as one has to match their fringing capacitance to permittivity and frequency for maximum sensitivity. Smaller probes are used for higher frequencies and permittivities. The flange is not essential but allows the probe to be fully calculable.

Radiated wave transmission, reflection or resonant techniques are actually used in materials processing, e.g. measuring moisture-content of a role of paper sheet in real time by feeding it through a microwave measurement cell. These techniques are good for thin materials. A variation might be measuring absorption in dielectric rods/tubes fed down the axis of a resonant cavity, from the cavity Q-factor. Resonant methods are best for low loss, transmission for high loss. The method can also be used in other areas such as for quantifying rainfall.

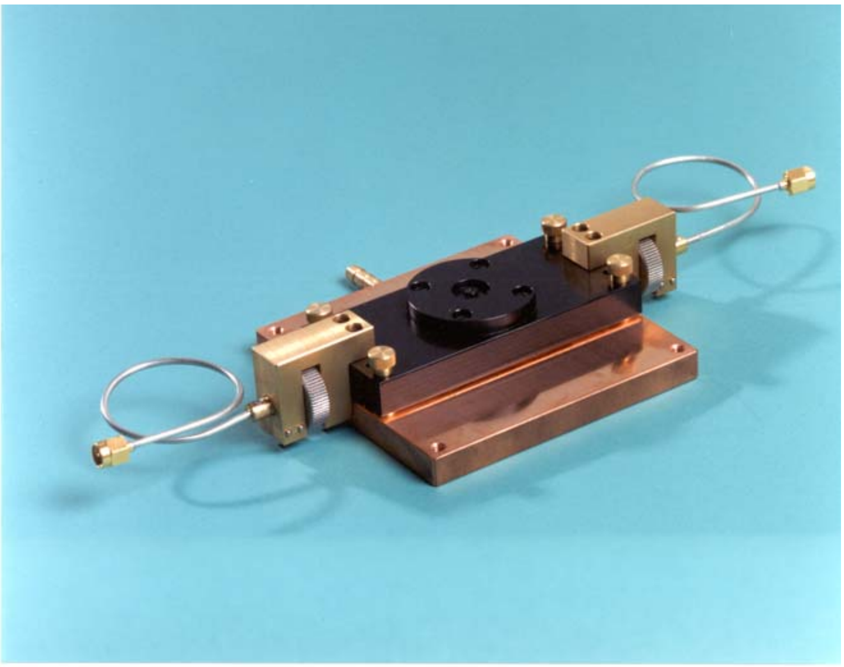


Figure 9: A 10 GHz split-post dielectric resonator, which can be used for monitoring the dielectric properties of strips of thin material which are inserted in the gap just above the copper plane. Typically used for measuring substrate materials in the frequency range 2 – 10 GHz.

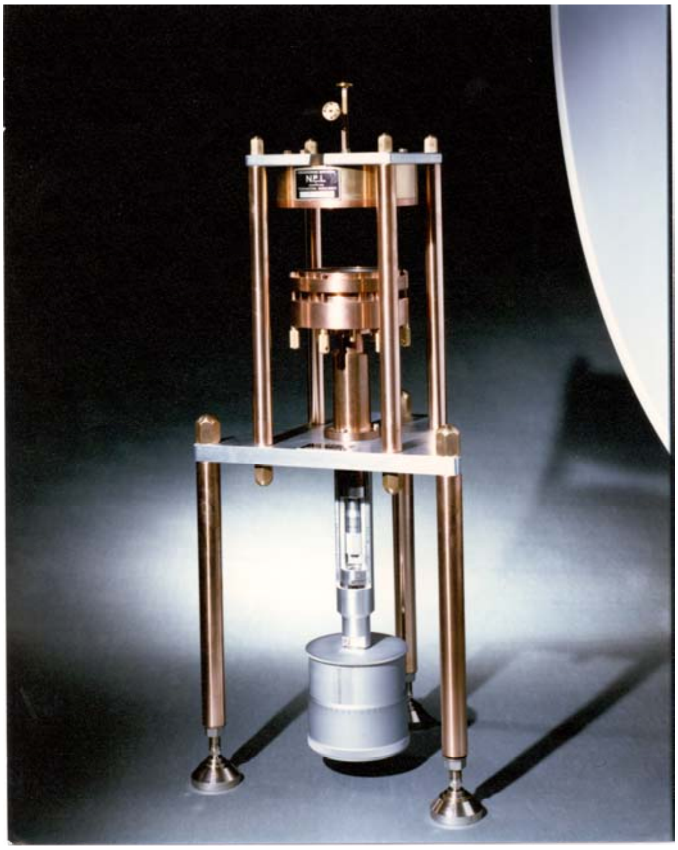


Figure 10: A 72 GHz open resonator for measuring dielectric properties in the millimetre wave region of the spectrum, typically 30 – 150 GHz.

In the case of the resonator shown in Figure 10, the dielectric under test, which takes the form of a lamina of arbitrary cross-section or a thin film, is introduced between the mirrors at the top of the instrument as shown and the microwaves resonate between the two mirrors. Dielectric properties are monitored through changes in the resonance frequency and the Q-factor of the resonance. Instruments similar to the one shown in Figure 10 have been employed for monitoring moisture in paper. NPL possesses a variant design which operates at 10 GHz and which has cantilevered mirrors so that the corners of large sheets of material can be tested non-destructively.

More sophisticated radiated signal techniques can also be considered. For example: radar, arguably, is a form of dielectric NDT and can also be used for measuring rainfall, etc. Other free field techniques include the measurement of insertion loss of laminas placed between two horn antennas. Going a step further, certain types of impedance, capacitance and dielectric tomography might be used for NDT purposes.

Contact:
Bob Clarke, CETM

3.4 Functional materials

The Functional Materials Group within MATC has investigated various scientific issues regarding the NDT/condition monitoring of functional and smart materials and structures. Examples have included the use of acoustic emission analysis from electrically excited piezoelectric ceramic materials. It has been shown that in multilayer piezoelectric actuators, the acoustic emission signal intensity depends on both sample heating and also multilayer degradation. The effect of mechanical fatigue on the acoustic emission is to reduce the AE output, suggesting there is little significant mechanical damage in the form of cracks, but that ferroelectric switching is being diminished, as shown in Figure 11.

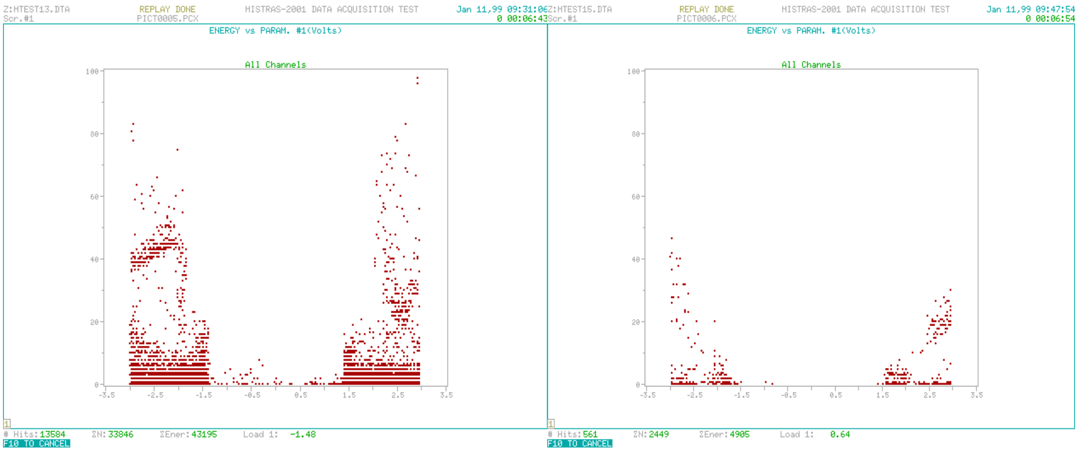
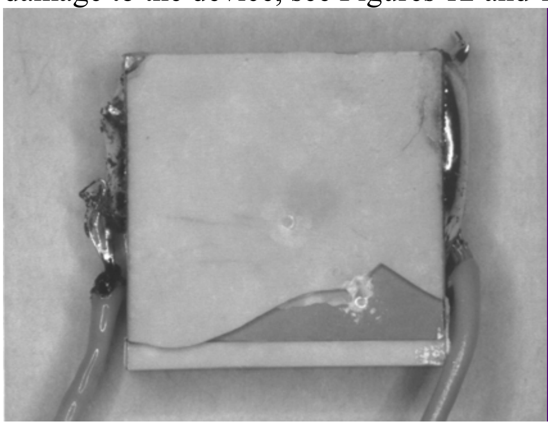
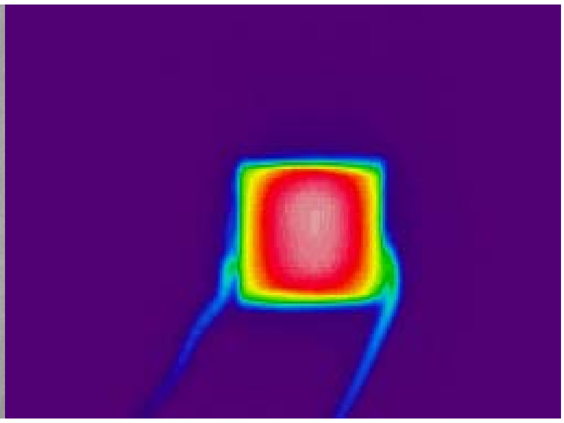


Figure 11: AE energy against driving field for a multilayer actuator. The left figure is for a virgin device and the right figure after 10^4 cycles of 30 MPa cyclic loading.

If damage within multilayer actuators is typified by interlaminar or electrode failure then it is possible that ‘hot-spots’ may result from localised heating caused by shorting electrodes or electrical discharges across the piezoelectric layers. Another technique adopted was to use thermal imaging to identify damage to multilayer actuators following mechanical damage to the device, see Figures 12 and 13.

Figures 12 and 13: Damage imparted to the multilayer actuator and the thermal signature while electrically driven

However in these exploratory measurements the thermal signature is dominated by the self heating throughout the thickness of the sample and the likelihood that a small ‘hot-spot’ in one layer will cause a change in the thermal gradient of the whole sample is small. In order to detect these defects a much more sensitive detection system will be needed, or perhaps the present methods could be used on much thinner devices, perhaps thick or thin film devices.

A final example of the NDT-type activity that the Functional Materials group within MATC undertakes is exemplified by the Faraday Partnership Flagship Research Project (1998-2002) - Acoustic Emission Traceable Sensing and Signature Diagnostics (AESAD). The research aims to create a sound scientific basis for the use of acoustic emission (AE) as a more reliable means of obtaining meaningful information about industrial machines, processes and materials, see Figure 14. The project will seek to produce a generic methodology that can be applied fairly readily, initially to a few exemplars from representative industries, with more general application to follow. Primary objectives are: to develop a robust scheme for traceable calibration of AE transducers; to develop a reliable means for signature analysis; to demonstrate the use of a novel methodology for traceable calibration of AE transducers in-situ in several diverse industrial applications; and to produce a set of guidelines on AE monitoring for diagnostic and control purposes. This project is being undertaken through Brunel University and brings together a collaborative group of nine industrial companies.

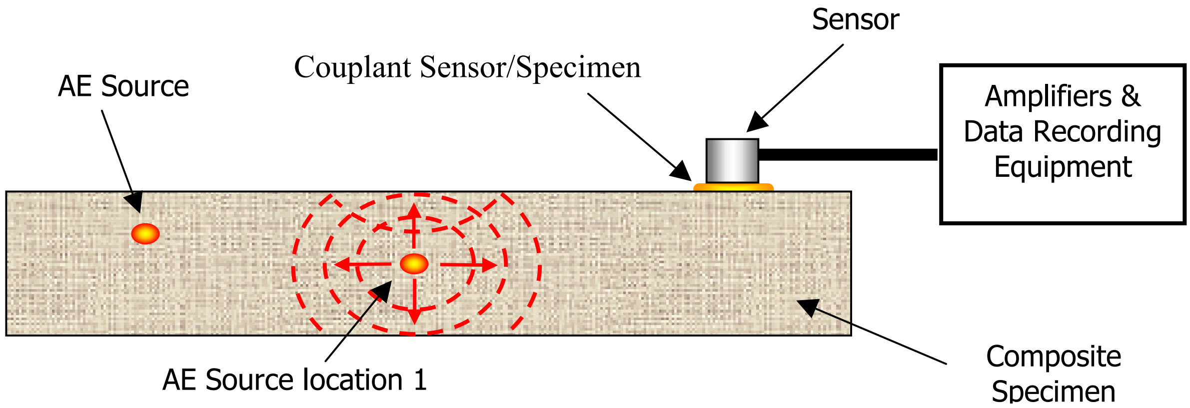


Figure 14: Schematic diagram of an AE set-up

See also http://www.brunel.ac.uk/research/bcmm/aesad/

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4 Cross-Centre Links

The table below shows the cross-Centre links between the different technical activities listed in Section 2. It should be noted that in about 40% of the cases more than one NPL Centre is actively involved.

Topic	NPL Centre						
	CBTLM	**CETM**	**CIRM**	**CMAM**	**CMSC**	**COAM**	**MATC**
AC conductivity		X					
Acoustic emission				X	X		X
Acoustic and ultrasonic transducer modelling				X	X		
Dielectric measurements		X					
Dimensional measurement	X						
Electronic speckle pattern interferometry							X
Fibre optic techniques	X						
Fluorescence						X	X
Fracture mechanics					X		
Impact excitation							X
Internal temperature measurement	X						
Laser-acoustic thin film analysis							X
Low relative magnetic permeability for NDE		X					
Magnetic and electrical NDE methods		X					X
Modelling and computational techniques				X	X		X
Neutron measurements			X				
Nuclear spectrometry			X				
Optical interferometry	X			X			
Photothermal technologies	X						
Properties of hard materials							X
Residual stress							X
Scanning acoustic microscopy							X
Signal processing				X	X		
Stress and structure - piezospectroscopy						X	X
Terahertz imaging		X					
Thermal imaging and analysis						X	X
Ultrasonics				X			X
Ultrasonic C-scanning				X			X
Ultrasonic transducer characterisation				X			
Ultrasonic properties of materials				X			X
Video extensometry							X
X-ray radiography and inspection			X				X

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