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STANDARDISATION OF PROCEDURES FOR ULTRASONIC INSPECTION OF POLYMER MATRIX COMPOSITES:

TRANSDUCER CHARACTERISATION AND MATERIALS EVALUATION

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ABSTRACT

The work described within this report was undertaken in support of a three year DTI-Aerospace Division funded project entitled "Standardised procedures for ultrasonic inspection of polymer matrix composites". The report gives a detailed account of the research work undertaken by the Centre for Mechanical and Acoustical Metrology (CMAM) at NPL, providing technical support and input in a range of key areas. In the field of transducer evaluation, an extensive comparison of small pulse-echo target and hydrophone based characterisation measurements has been completed. The utilisation of CMAM's unique high spatial resolution, wide-bandwidth membrane hydrophones has, for the first time, demonstrated that the propagation of ultrasound generated by NDT transducers is a nonlinear process. The implications of the resultant waveform distortion for field characterisation measurements as well as for the absolute determination of material attenuation have been assessed. A preliminary attempt to model the effect of nonlinear loss on C-scan attenuation measurements has been made, the results being compared with experiment. The report also describes a number of other studies carried out within the project to underpin several key technical areas. These include a systematic investigation of the effect of collimation on the transducer field as well as extensive measurements made to determine the ultrasonic properties (attenuation coefficient, phase velocity) of a range of materials important to the project.

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0 EXECUTIVE SUMMARY

This document constitutes a detailed account of the research work carried out by the Centre for Mechanical and Acoustical Metrology (CMAM) at NPL during a three year project funded by the UK Department of Trade and Industry (Aerospace Division). The project as a whole addressed key aspects of the standardisation of ultrasonic C-scan procedures, as applied to the industrial inspection of polymer-matrix composite materials.

The central objective of the three-year collaborative project involving the Structural Materials Centre - Defence Evaluation and Research Agency (DERA), the Centre for Materials and Measurement Technology (CMMT) - NPL, and CMAM was to develop three draft procedures. A brief overview of each is given:

Part 1: Draft Operational Procedure

This document describes the procedures to be used in the C-scanning of polymer matrix composite materials on the workshop floor. It specifies three principal methods of C-scanning, namely pulse-echo, single through-transmission and double through-transmission. Specifications are given for immersion, contact, and squirter testing, and the procedure describes the implementation of these methods for defect sizing and for the measurement of transmission loss in materials. The use of collimators is described, and requirements placed on their performance.

Part 2: Draft Calibration Procedure

This document describes procedures for the testing and calibration of the transducers used in C-scanning of composite materials. It covers the areas of spatial beam characterisation, and of frequency determination, using pulse-echo and hydrophone-based measurement techniques. Consideration is given to areas such as nonlinear propagation and spatial averaging, and the effects these may have on the determination of transducer parameters.

Part 3: Preparation of reference defects and reference panels

This document provides specifications and procedures for the design and realisation of standard polymer matrix composite panels for testing C-scan system performance. It covers the preparation and implementation of standard defects, and includes guidelines on suitable materials for both panels and defects, and requirements on the manufacturing processes required to produce panels to meet these specifications.

Reference is made in several Sections of this report to the Part 1 and Part 2 draft procedures, which are those described above. CMAM's role in the project was principally in the production of the draft Part 2 procedure, where it was to undertake the technical work required to underpin the document, enabling its acceptance.

Conventionally within the field of nondestructive testing (NDT), transducer characterisation is carried out by recording the pulse-echo response of the transducer to a small target scanned through the transducer field. The majority of Standards which do exist prescribe the use of spherical targets (small ball-bearing scatterers) for this purpose. However, the most recent standard, ASTM E 1065-92, does permit the use of miniature hydrophones to interrogate the transducer field. Within this study, CMAM utilised a range of polyvinylidene fluoride (pvdf) membrane hydrophones whose high spatial resolution and wide bandwidth (> 50 MHz) enabled the true acoustic waveform produced by the NDT transducer to be recorded. This is in direct contrast to the bandwidth-limited response

observed when the transducer is operated in pulse-echo mode. The work presented constitutes the first systematic comparison between pulse-echo and hydrophone-based methods for measurements on commercially-available NDT systems. A number of important findings have resulted from this work.

At the frequencies and acoustic pressures produced by C-scan transducers, propagation of the ultrasonic pulse through the water bath surrounding the component under test cannot be regarded as a linear process. The acoustic waveforms measured by the membrane hydrophone demonstrate pressures as high as 10 MPa (peak-compressional) and strongly distorted acoustic waveforms, where the peak-compressional and peak-rarefactional pressures are asymmetrical and differ in some cases by a factor of four. Viewed in the frequency domain, the distorted waveform contains many harmonics (multiples) of the fundamental frequency of the pulse, extending beyond 70 MHz. Another consequence of the nonlinear distortion is the enhanced loss of the fundamental frequency component, and this has important implications for any attempts to determine the attenuation coefficient of a material on an absolute basis. This topic will be returned to later within the Executive Summary.

One of the critical aspects of the study was to assess the influence of nonlinear distortion on the measured transducer parameters of interest, principally the beamwidths obtained at the position of the last-axial maximum for unfocused transducers (Y_{0+}), or at the focus for focused transducers. In principle, hydrophone and pulse-echo measurements should provide equivalent measurements for the beam characteristics (both radial and cross-axial) providing two criteria are met: that the spatial-resolution is the same i.e. that they behave as point receivers and point targets respectively, and that the overall measurement bandwidth of the two systems is identical. The second of these can be met by applying low-pass filtering to the broadband hydrophone signal to remove the higher harmonics from the time-domain waveform, thereby ensuring that they do not contribute to the measured spatial parameters.

The ASTM document states that beam parameter measurements made using a hydrophone and ball target are directly equivalent, providing that they are evaluated at the -6 dB level (for the pulse-echo measurement) and the -3 dB level (for the hydrophone measurement). Through a series of careful measurements on several NDT transducers, this relationship has been validated for both unfocused and focused transducers. However, the beamwidth determined for focused transducers appears to depend more strongly on the dimensions of the ball target used. The reasons for this are uncertain and require further work, but probably arise from spatial-averaging of the wavefronts of the focused field over the surface of the ball target.

The issue of ball target specification for pulse-echo measurements has been addressed through several routes. A relatively simple model of the behaviour of such a target in the field of an unfocused transducer has been developed and this indicates that the active surface of the ball target is actually small. At the specific distances used for characterising the transducer beamwidths (Y_{0+}), even fairly large diameter targets (> 5 mm) represent reasonable approximations to point scatterers. This behaviour has been confirmed using an analysis of the anticipated response of a pulse-echo transducer to an idealised point target. Experimentally, these conclusions have been validated through a series of systematic measurements on a range of NDT transducers using both ball targets and hydrophones.

When ball targets are used to determine transducer beam parameters close to the transducer, strong peaks in the response arise, the work presented here confirming the earlier findings of DERA. This peaked response arises due to the complex interaction between the plane and edge-wave components of the transducer field and the ball target, but in the cases observed, these only arise at relatively small transducer-target separations, $< \frac{1}{2} Y_0$. For determination of the pulse-echo axial response and the identification of the last-axial maximum, this phenomenon should not be important.

However, in situations where near-field parameters need to be derived, it is more appropriate to use disc targets formed by flat-ended rods, as these do not appear to be prone to the edge-wave enhancement effect observed for ball targets. Within this study, a range of targets of this type have been used to characterise the transducer field and their results are compared with those of both hydrophones and ball targets.

To underpin the specification of pulse-echo target (ball or disc) or hydrophone dimensions, a series of numerical calculations have been carried out using a plane-piston model of the transducer field. These have been used to assess and control the error in the beamwidth measurements produced by spatial-averaging of the pressure over the surface of the small target or hydrophone.

Earlier within this Executive Summary, the influence of nonlinear loss of the fundamental frequency component on measurements of ultrasonic attenuation was highlighted. In situations where the absolute attenuation coefficient of the polymer material is being investigated, the resultant enhanced attenuation can give rise to significant errors. This loss is dependent on the acoustic pressure at the face of the transducer, whether the transducer is focused or not, details of the specimen, and the relative separations of the transducer and specimen. A theoretical model is developed which is used to assess the influence of nonlinear loss on attenuation measurements using a particular C-scan configuration: the Front Wall Echo (FWE) - Back Wall Echo (BWE) method. The model has been tested using two highly parallel reference specimens whose acoustical properties are similar to those of carbon-reinforced composites. Encouraging qualitative agreement is displayed between theory and measurement. Ancillary measurements performed indicate that, for band-limited systems, the reflection from a highly polished stainless steel surface monitored close to the transducer face may be used to derive a value for the nonlinear loss occurring in any measurement situation.

Results are also presented in this report of an investigation into the effect of collimators on the acoustic field of an NDT transducer. A systematic study of the relationship between the collimated field and the specification of the collimator used has been carried out. The results indicate that, broadly, the collimated transducer can be approximated by a transducer whose effective diameter is equal to that of the collimator aperture. The effect on the positioning of the new last axial maximum and the improvement in spatial resolution has been investigated in detail. This study is of particular importance to the C-scan Part 1: Operational Procedure.

1 PROJECT OVERVIEW

During the course of the project, CMAM acted as a subcontractor to the co-ordinator, NPL-CMMT. Although its general remit was to provide reference measurements designed to underpin a number of key areas of research, the aim was also one of contributing specifically to several distinct deliverables identified in the original project proposal. These are listed in Table 1, alongside references to the particular Section of the current report where this work is described in detail.

Table 1.1: Summary of the work areas undertaken by CMAM in support of the project deliverables D2, D3, D5 and D7, presented alongside a reference to the appropriate text where the work is described in detail.

Deliverable identifier	Deliverable description	Relevant Section of current report	Description of work
D2	Report on assessment of operational and calibrational procedures	Section 2.	Completion of Standards review.
D3	Draft Part 1: Operational procedure	Section 8.	Systematic investigation of the way in which the collimator influences the acoustic field.
D5	Draft Part 2: Calibration procedure	Section 4.	Investigation of the acoustic pressure waveforms generated by NDT C-scan equipment using wide-bandwidth hydrophones.
		Section 5.	Study of methods for determining the frequency response.
		Sections 6 and 7.	Beam profiling using hydrophones and small point-like pulse-echo targets.
D7	Initial assessment of the effects of the acoustic properties of the system on measurements	Section 9.	Material acoustic property measurements on a range of reference materials.
		Section 10.	Assessment of influence of nonlinear propagation on absolute attenuation measurements in support of DERA programme.

2 SUMMARY OF CURRENT STANDARDS

2.1 OVERVIEW

The primary aim of NPL-CMAM's input to the project was to produce a draft procedure for the calibration of the ultrasonic transducers used in C-scanning of composites. Given that the ultrasonic inspection of structures is a long-established practice, and that Standards relevant to transducer testing exist, it was considered essential to review the current Standards scene at an early stage in the project. This review provided the basis for certain parts of the experimental programme involving the validation of test methods, but also served to identify the technical areas requiring targeted investigation.

Within the current Standards arena, there are many documents concerned with the application of C-scan ultrasonics to NDT. The majority of these refer to scanning practices, terminology and definitions. There are comparatively few Standards that address the issues of transducer and system characterisation and many of those which do exist recommend the use of reference blocks. This Section summarises the three key Standards in this field. Additionally, a description is given of a guidance document produced by Panametrics, a prominent transducer manufacturer. Finally, there are a range of IEC Standards that refer to the assessment of the acoustic output characteristics of medical ultrasonic equipment using hydrophones, and the document most appropriate to the current project has been summarised.

2.2 ASTM E1065-92: STANDARD GUIDE FOR EVALUATING CHARACTERISTICS OF ULTRASONIC SEARCH UNITS

Document overview

The Standard contains measurement procedures for evaluating characteristics of immersion transducers in the frequency range 0.4 MHz to 10 MHz (the "search units" in the title). Rather than setting performance and acceptance criteria, it simply defines a range of means for obtaining performance data that may be used to define the acoustical and electrical responses of ultrasonic search units. The procedures are intended for the measurement of focused and unfocused transducers as individual components (separate from the ultrasonic test set) using commercial characterisation means (such as scanning tanks, with 5 degrees of freedom) and conventional laboratory equipment. Broadly, the document is divided into two distinct parts, and these address the assessment of electrical and acoustical characteristics respectively.

Electrical measurement procedures

The first part of the Standard encompasses the measurement of frequency parameters, and describes the use of either shock excitation or sinusoidal burst (swept through a range of frequencies successively) to drive the transducer. Guidelines are given on parameters such as the drive unit and transducer impedance to minimise the effect of pulser characteristics on the measured response. In both excitation regimes, a flat and smooth glass block reflector of dimensions 50 × 50 × 25 mm is used, and the frequency characteristics quoted are hence pulse-echo in origin. Unfocused transducers are set up at 50 mm separation, whilst focused devices are adjusted to produce the maximum echo level. The shock excitation and sinusoidal burst techniques are used to measure the pulse-echo sensitivity and time response respectively.

Acoustical measurement procedures

The measurement of the sound field parameters, which describe the way in which ultrasound is distributed in the transducer field, is performed using an immersion technique. The document is unique in allowing the use of both piezoelectric hydrophones and pulse-echo targets for these measurements. It suggests that the data obtained using the two methods may be considered equivalent, provided that figures for the pulse-echo case are quoted at the -6 dB level, and hydrophone data is quoted at the -3 dB level. These levels apply to parameters such as the beamwidths and focal zone.

Specifications are provided on the dimensions of the measurement devices used: 5λ to 10λ (where λ is the wavelength of ultrasound in water) in the case of the ball target (whether this is the diameter or the radius is not clear), and 2λ for the diameter of the active element of the hydrophone. Additionally an important requirement for the frequency response of any hydrophone identified is that it must be sufficiently broad so as not to introduce any adverse response into the system. If a conventional miniature hydrophone is not available, it suggests the application of a collimating mask to a conventional transducer to produce a high resolution "hydrophone". For unfocused transducers, the parameters identified for measurement are aperture size, traverse profile, on-axis profile and sound beam spread. For focused transducers, focal length, depth of focal zone and focal point diameter are added to the list.

Frequency downshift

The Standard addresses the problem of frequency downshift seen with high frequency transducers with large bandwidths when used at large stand-off distances, providing a look-up table and several equations for corrections that may be applied to account for this. Frequency downshift may also reduce the effective focal length of focused transducers. Section 5.2 presents an assessment of the importance of frequency downshift in the context of the current project.

For cases where frequency downshift is likely to be significant, a series of alternative measurement configurations are suggested, which consist of inserts placed in the water path, or using solid materials containing pulse-echo targets, the net effect being to reduce the total effective propagation path. A distinction is also made between the focus measured using a planar reflector (flat-plate focus) and that measured using a ball pulse-echo target (point-target focus), according to their assessment via the axial dependence of the maximum positive or negative peak half-cycle amplitude with the transducer operating in pulse-echo mode.

Finally, the document includes diagrams throughout, which provide simple schematic representations of many of the concepts described.

2.3 SAE AS 1355 (1974) ULTRASONIC TRANSDUCERS, IMMERSION AND CONTACT: PERFORMANCE PARAMETERS

Document overview

The document "provides a means for establishing a uniform method for specifying and standardising ultrasonic immersion transducer performance, and controlling allowable tolerances for procurement specification." It identifies and defines transducer performance

parameters and describes methods for measuring each parameter. Unfocused and focused single element transducers are covered. A scanning tank system is recommended with 3 perpendicular axes of movement, and a "normalizing device" is required for initial system alignment.

Electrical measurement procedures

For the testing of frequency parameters, the use of a flat reflector (surface finish specified at 63 microinches, equal to $1.6\text{ }\mu\text{m}$), the size of which must be greater than twice the sound beam diameter is recommended. Requirements are set on the characteristics of the pulser (negative spike of 75-200 V, -3 dB bandwidth (into $50\text{ }\Omega$) of 0.1 - 40 MHz, pulse repetition rate of approximately 1000 Hz), the receiver (-3 dB bandwidth of 1.0 - 40 MHz, controllable gain from 0 to 60 dB in ± 1 dB steps which is flat to ± 0 , -3 dB across the bandwidth) and the spectral analysis electronics (bandwidth 1.0 - 40 MHz, oscilloscope-type display). Methods are given for determination of the damping factor and the sensitivity of the transducer.

Acoustical measurement procedures

For sound beam profiling, ball target reflectors are recommended whose diameters vary with the frequency of the transducer and are given in Table 2.1. The targets should be constructed from precision-ground corrosion-resistant steel, and then mounted on a conical pedestal.

Table 2.1: Recommended ball pulse-echo target diameters for beam profiling, from SAE AS 1355 (1974).

Transducer frequency (MHz)	Ball diameter (mm)
0.5 - 1.0	10
1.0 - 2.5	5
2.5 - 20.0	3

The measurements required are those of beam symmetry, beam diameter and focal length or the position of the last axial maximum for unfocused transducers (which will be denoted by the symbol Y_{0+} in the remainder of the document). A flat target is used for axial profiling of unfocused transducers, and as with the frequency measurements, the size of this must be greater than twice that of the sound beam diameter, to minimise target directivity influences.

Measurements of the beamwidth are required to be made in the focal or Y_{0+} plane, and also at half this distance. A table is included which gives percentage tolerances (in comparison with specification) on frequency, bandwidth, damping factor, sensitivity, beam diameter and focal distance or Y_{0+} . The three tolerance levels suggested (typically 5, 10 or 15%, depending on the parameter) denote the appropriateness of a transducer for purpose at three different specification levels, which would be decided upon by the user. The document also states that the immersion-based beam-profiling techniques may be extended to cover measurements of contact probes, and includes illustrations of test blocks that may be used.

2.4 MCDONNELL DOUGLAS CORPORATION DPS 4.738-2 (REV. 1988): ULTRASONIC INSPECTION OF COMPOSITE STRUCTURES

Document overview

The document is actually a process standard, which specifies the requirements and instructions for pulsed ultrasonic inspection of composite structures, but also includes some limited recommendations and a few test methods for the characterisation of ultrasonic transducers. An initial requirement is set which states that only spherically focused search units may be used for immersion testing, although flat and focused devices are permitted for squirter testing. Hence this restricts the scope of the document in terms of the requirements for transducer characterisation.

Another note of interest from this Standard is its reference to the use of collimated transducers. Strictly, this is relevant to the Part 1: Operational procedure but is appropriate to the work undertaken by NPL-CMAM on collimators presented in Section 8. The McDonnell Douglas Standard allows the use of such collimators but only over a certain range of distances which in any configuration (transducer-collimator combination) is determined through scans on a "gold standard" reference defect. The rationale behind this will be considered in Section 8.

Electrical measurement procedures

Determination of the spectral response of transducers must be performed, specifically for measurement of the peak frequency and the -6 dB bandwidth, although a method is not given. A distinction is then made between "narrow band" (bandwidth $\leq 45\%$) and "wide band" ($> 45\%$) transducers. For the narrow band case, acceptance levels are specified on the measured peak frequency compared to the nominal peak frequency: $\pm 10\%$ for transducers ≥ 5 MHz, 20% for transducers of 2.25 MHz, 25% for transducers of 1 MHz. Similarly, all wideband transducers must fall within a $\pm 30\%$ limit of the specified frequency.

Acoustical measurement procedures

All search units are required to be beam profiled. Suitable techniques are specified, with distances at which scans should be performed. In all cases, the recommended pulse-echo target is a $0.25"$ (6.35 mm) diameter steel ball, and for unfocused transducers, a $0.078"$ (1.98 mm) flat-bottomed hole formed in an aluminium block is also permitted. For focused transducers, axial profiling is required for determination of focal position and the effective focal zone, which is defined at the -6 dB level. A $0.25"$ (6.35 mm) steel ball is also used for this. The resolution for axial scans is defined, in terms of $1/8$ of the signal height at the focal point, and similarly, $1/8$ of the water travel distance to the focal position. A look up table is given which provides nominal Y_{0+} distances in water, and provides a conversion factor for determining the Y_{0+} position when using a flat-bottomed hole, due to the difference in sound velocity in aluminium compared to water.

Cross-axial beam profiling of focused transducers is required in two perpendicular directions, and the smaller of the two values returned at the -6 dB level is taken as the sound beam diameter. Requirements are set on the transducer beamwidths measured: a $0.5"$ (12.7 mm) diameter transducer shall have a beam diameter not greater than $0.090"$ (2.29 mm), and a $0.75"$ (19.05 mm) diameter transducer shall have a beam diameter not greater than $0.200"$ (5.08 mm). For all transducers, a cylindrical symmetry criterion of better than 75% is set for cross-axial beamwidths. An inspection of transducers must be made annually.

2.5 PANAMETRICS DOCUMENT 'IMPORTANT CHARACTERISTICS OF ULTRASONIC TRANSDUCERS AND FACTORS RELATED TO THEIR APPLICATION'

Document overview

Rather than being a standard, this document instead seeks to clarify what is perceived to be some confusion regarding definitions of beam parameters and characterisation techniques. It includes a range of informative diagrams, and a series of useful equations, including some fundamental theory relating to ultrasonic wave propagation. The concepts behind the terminology of Y_{0+} are given, and a simple qualitative description of field distributions is also provided. In measurement terms, specific techniques are not given: however, use of a small ball reflecting target or a hydrophone is suggested for beam profiling, with recommended diameters of 10λ and 0.5λ respectively. The use of the pulse-echo target is recognised as being more commonplace, and the relationship between the two measurement methods is described in terms of the -3 dB hydrophone data being equivalent to -6 dB pulse-echo data when measured in an identical plane of the acoustic field.

Effect of system parameters

A simple assessment is given of the effect of transducer bandwidth on measured sound field parameters, with estimates given for the expected shift in the position of the on-axis maximum, depth of field etc. as a function of the transducer bandwidth. Further, it is recognised that the presence in the acoustic waveform of many frequency components (due to the drive conditions typical of flaw detectors) may have significant effects on the measured beam parameters, and may also smear characteristic features of the beam profile that would be evident in a single excitation frequency case.

Focused transducers

Focused transducers are also considered in detail, with equations and graphs describing the effect of using acoustic lenses as well as contoured elements. The true focal distance is described as being best evaluated using a ball target: however, distinction is made between this and the "flat plate focus", which is considered easier to measure. A description is given of the on-axis trends seen when using a flat target for profiling: for unfocused transducers, the increase in signal amplitude at Y_{0+} is very low, so much so that, for larger transducers operating at higher frequencies, there may be no discernible peak in the flat plate case. This is described as being due to the offsetting effect of attenuation in water with increasing range. The Section on focused transducers also contains equations predicting the pulse-echo beamwidths, and contains a theoretical assessment of transducer sensitivity.

2.5.4 Frequency downshift

The problem of frequency downshift described by the ASTM document is also discussed, with a similar look-up table providing information on frequency, bandwidth and the maximum permissible water path. For transducers falling outside the guidelines, a strategy of using a shorter water path and a second material (e.g. fused silica) is recommended. It is suggested that this is the simplest technique by which the flat plate focus may be measured.

Generally, the document contains a lot of useful information which in comparatively straightforward terms outlines the effects that certain transducer parameters are likely to have

on field characterisation, and also attempts to guide the user through measurement techniques that will uncover and to some extent allow for these problems. It is likely that the description given in the guidance document for comparing results in the hydrophone and pulse-echo cases, and the detailed Section on frequency downshift was actually used in the production of the ASTM document.

2.6 IEC STANDARDS

A number of International Electrotechnical Commission (IEC) Standards have been published which relate to the measurement of the acoustical characteristics of medical ultrasonic devices. The requirement of accurate measurements which are traceable to National Standards has been driven principally by safety issues in the use of medical ultrasound.

The work presented in this report leans heavily on the use of these IEC Standards in terms of specifying the acoustic parameters of interest and in the use of hydrophones to characterise the acoustic field. The key document in this area is summarised here.

2.6.1 IEC 1102

IEC 1102, entitled "Measurement and characterisation of ultrasonic fields in the frequency range 0.5 MHz to 15 MHz" was published in 1991. Its main purpose is to define various acoustic parameters which can be used to specify and characterise ultrasonic fields propagating in liquids, and in particular water, using hydrophones. Measurement procedures are outlined which may be used to determine those parameters. It is based on the specification of the acoustic field in terms of acoustic pressure and other quantities which may be derived from it.

As with all IEC Standards, a series of cascading definitions are provided, along with symbols and units required. The document contains detailed specifications on the choice of hydrophone for a particular measurement, in terms of minimising spatial-averaging effects and maximising system bandwidth. Specifications and requirements are provided for positioning systems, and a comprehensive description of aligning the system prior to measurements is given. The document is aimed at the derivation of parameters considered important in the field of medical ultrasonics, namely values for spatial and temporal-peak and temporal-average acoustic intensities, with the outcome being the acoustic output specification of a medical device. It is relevant to NDT systems, as it describes the application of hydrophones to field measurement in general terms. It is useful to consider also the fundamental calculations performed on acquired acoustic signals which are contained in IEC 1102, and a brief synopsis of these can be found in Appendix D.

3 MEASUREMENT SYSTEMS AND EQUIPMENT

This Section describes the experimental systems utilised during the project and includes a description of both the facilities and the range of measurement devices used. Throughout its duration, extensive use was made of many of the experimental facilities in NPL-CMAM, and principal amongst these was the facilities dedicated to beam-plotting and materials characterisation. An important feature of NPL-CMAM's contribution to the project was the use of a wide variety of hydrophones. Additionally, an extensive series of pulse-echo targets were designed and manufactured. A typical NDT pulser-receiver and series of transducers were obtained from one of the manufacturers represented within the Industrial Advisory Group, and these were used as the "reference" sources during the validation of the various experimental methods. Additionally, in order to extend the range of systems on which measurements were made, a commercially-available flaw detector was obtained on loan from DERA, along with 4 transducers.

3.1 THE NPL BEAM-PLOTTING FACILITY

This facility has been described in detail elsewhere¹, and so only a brief overview will be provided here. The system comprised a water tank of dimensions 80×40×40 cm, which was mounted underneath a gantry. The gantry supported two independent mounts, both of which had three orthogonal linear axes and two orthogonal rotational axes, giving ten degrees of freedom in all. A spatial resolution of 2.5 μm was available. The transducer under test was fixed in one mount, and the hydrophone or pulse-echo target in the other. The output connection from any hydrophone used in the measurements was fed to an amplifier (see Table 3.3 for the various combinations used), and in turn to a calibrated digitising oscilloscope. The digitised signal was then fed to a HP 9000 series 200 workstation for analysis and storage. The complete acquisition and positioning system was computer controlled.

3.2 THE NPL MATERIALS CHARACTERISATION FACILITY

The NPL materials characterisation facility was designed and developed specifically to enable measurements of the ultrasonic properties of materials to be made using a broadband through-transmission substitution technique. To this end, it is possible to identify a number of important properties of the facility which affect measurement capability and accuracy and these are outlined briefly here.

3.2.1 Positioning hardware and temperature control system

The transducer, specimen under test and ultrasonic receiver are suspended in a test tank containing degassed and deionised water. Standard micropositioning mounts enable these three components to be independently manipulated and accurately coaxially aligned. Tilt and rotational adjustments are provided to orientate the specimen to ensure that its surfaces may be accurately aligned relative to the face of the transducer. Identical positioning capability allows pulse-echo measurements of attenuation to be made using a comparison of the front-wall echo (FWE) and back-wall echo (BWE) reflections as described in Section 10. In addition, the specimen may be swung in an arc, removing it completely from the acoustic beam and returning it to its original position to within $\pm 0.5 \text{ mm}$; a special feature which reflects its use for through-transmission substitution measurements. A further property of the facility which makes an important contribution in studying and assessing the influence

of systematic effects such as diffraction and nonlinear propagation (Section 10), is the ability to vary the relative separations of the transducer, specimen and receiver.

Material attenuation and propagation speed are commonly strongly temperature dependent and this places stringent requirements on both its control and measurement. A temperature control system, coupled to the water contained in the test tank via heat exchange coils, enables the temperature of the material being measured to be varied within the range 5 °C to 40 °C. A platinum resistance thermometer, positioned close to the specimen, enables the temperature to be measured to within $\pm 0.1^\circ\text{C}$.

Transducer drive system

The transducer used to interrogate the specimen under test was a broadband transmitter manufactured by the Medicoteknisk Institute (Denmark). With a nominal active element radius (a_t) of 5 mm, the transducer operated as a thick crystal device providing a short duration acoustic pulse of the required bandwidth. The transducer was driven by a triggered electrical pulse from a function generator whose rise-time was 20 ns. The peak electrical drive voltage applied to the transducer for materials property measurements was typically 18 V. This relatively low value is an important characteristic of the NPL materials characterisation facility as the low acoustic pressure levels generated (< 20 kPa peak) minimise any systematic measurement uncertainties arising from nonlinear distortion through the water path.

Detection and signal analysis system

With the need to make measurements of attenuation and propagation speed over as wide a frequency range as possible, in developing the NPL Materials Characterisation Facility, particular emphasis was placed on the amplification of the electrical signal generated by the receiver. The low acoustic pressures generated rendered this particularly important. This signal-to-noise ratio enhancement was achieved in a number of ways. Piezoelectric hydrophones of large aperture were utilised; 4 mm and 30 mm active element PVDF (polyvinylidene difluoride) bilaminar shielded membrane hydrophones manufactured by GEC-Marconi were used (as mentioned in Section 3.4, the key feature of the hydrophones relevant to the present study is their wide-bandwidth, which for devices used for materials property measurements, is approximately 20 MHz). The electrical signal from the hydrophones was further amplified using a cascaded filter combination which provided 40 dB of gain and employed a 20 MHz low pass filter. Overall, the -6 dB measurement bandwidth of the combined transmit-receive system was typically 12 MHz.

The amplified hydrophone output voltage was digitised using a Tektronix 7854 DSO, the acquired waveform being transferred to a Hewlett-Packard 9000 series 200 workstation for FFT analysis and information storage. Acoustic waveform acquisition is typically carried out using a time-window length of 2 μs , this being of sufficient duration to record all of the important acoustic information.

A Tektronix DC5009 counter-timer was used to provide accurate measurements of the 'coarse' time-delay required for propagation speed measurements. Under the control of the HP workstation, the DC5009 was used to determine the time elapsed between the electrical trigger being applied to the transducer and the initiation of the time-acquisition window of the DSO. To ensure good statistics and a resolution better than 0.1 ns, 10000 acquisitions of the time-delay were acquired. For certain materials, in particular those characterised by a

high velocity mismatch with water (which is characteristic of composite materials), the insertion of the specimen into the acoustic beam will result in a shift of the acoustic waveform out of the acquisition window. In this case, the transmitted pulse is repositioned by applying an appropriate time delay to the start of the time-window whose value is accurately determined using the DC5009.

3.3 NDT SYSTEMS MEASURED

3.3.1 Systems owned by NPL

The majority of the transducers measured were supplied by Meccasonics, and driven using a pulser-receiver from the same manufacturer. In some instances (for example Section 6.5), other transducers were used with the same drive unit. The transducers measured comprised a wide cross-section of focused and planar devices typically used in NDT, with frequencies in the range 1 to 10 MHz and crystal diameters from 6 to 15 mm. Table 3.1 provides a list of the specifications. All transducers were manufactured by Meccasonics unless stated. A comprehensive set of reference data for the Meccasonics devices can be found in Appendix A. The Meccasonics pulser-receiver was designed such that the complete range of transducers available could be used, by having an output selector which corresponded to the nominal centre frequency of the transducer being driven. The ranges covered were 0.5 - 10 MHz and 10 - 30 MHz: the drive waveform in each case was a negative spike, with the peak voltages generated being approximately 600 V and 350 V respectively, measured using an oscilloscope directly. Many of the Standards reported in Section 2 describe a calibration test for drive systems, which requires the measurement of the drive pulse into a calibrated 50 Ω load. Figures 3.1 and 3.2 show such measurements, for the drive waveforms at the low and high frequency settings respectively.

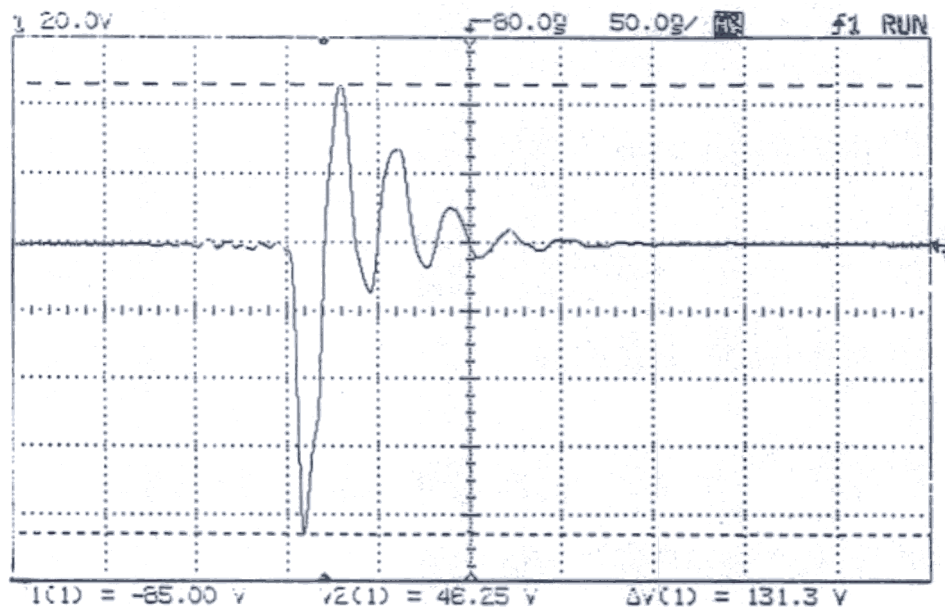


Figure 3.1: Meccasonics drive unit electrical waveform measured into 50 Ω for the low frequency setting (0.5 to 10 MHz)

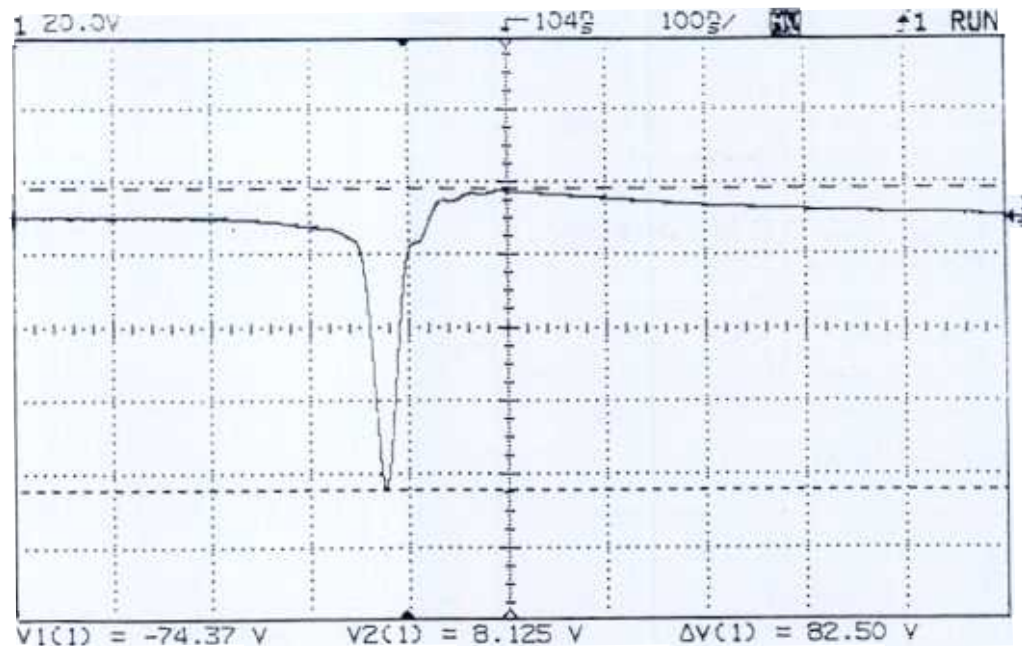


Figure 3.2: Meccasonics drive unit electrical waveform measured into 50Ω for the high frequency setting (10 to 30 MHz)

Note that the peak voltages are significantly less than those seen in direct oscilloscope measurements: this is indicative of the large difference in electrical impedances of the load (50Ω), compared to the oscilloscope (approx. $1\text{ M}\Omega$). The Meccasonics transducers used typically had impedances of 10Ω .

The Meccasonics pulser-receiver was nominally identical to that employed in the C-scan system used by NPL-CMMT during the project, meaning that transducers characterised in CMAM could then be connected to the CMMT C-scan rig, with the accurate reference data available for field distributions, frequency spectra etc. still being applicable. However, even with nominally-identical drive systems, small differences in characteristics such as the output electrical impedance can have significant effects on the fields and acoustic pulse waveforms produced by the transducers employed. To investigate the extent of such effects present in the two systems, a short series of investigations was carried out using a hydrophone, amplifier and oscilloscope system to compare the fields produced by the transducers when used in the NPL-CMMT system against their performance when driven using the NPL-CMAM unit. This was undertaken for a range of devices. In all cases, agreement in the hydrophone-derived data was better than 10%.

Table 3.1: Specifications of Meccasonics transducers used

Serial number	Nominal centre frequency (MHz)	Type (nominal focus, mm)	Crystal diameter (mm)	Note
F1655	2.5	unfocused	10	
F1657	1	unfocused	15	
F1658	10	unfocused	10	Replaced in latter stages
F01951170	5	focused, 50	10	Repaired during project
F01951172	1	focused, 50	15	Repaired during project
F01951173	2.5	focused, 50	10	
F10941099	10	focused, 50	10	
F11941135	5	unfocused	10	
F11941136	5	unfocused	10	
99589	5	unfocused	6.35	Panametrics transducer

3.3.2 System obtained on loan

During the course of the project, it was considered beneficial to measure a complete flaw detector actually used in C-scanning. To this end, an Krautkramer Branson USIP20 HR was obtained on loan from DERA, together with four KB-Aerotech transducers used by them on a regular basis. These are described in Table 3.2. Although the system was available only for a brief period, a series of reference hydrophone characterisation measurements were conducted. These can be found in Appendix B.

Table 3.2: Specifications of KB Aerotech transducers used with the KB flaw detector.

Serial number	Nominal centre frequency (MHz)	Type (nominal focus in mm)	Crystal diameter (mm)
007406	5	unfocused	12.7
D12559	2.25	unfocused	12.7
"10F"	10	focused, 38	9.5
001401	10	focused, 76	9.5

3.4 MEMBRANE HYDROPHONES

NPL-CMAM has access to a large selection of membrane hydrophones manufactured by GEC-Marconi, which were used extensively throughout the project. There are a number of properties of these hydrophones which made them important to the project, principal amongst these being their large bandwidth and high spatial resolution. The membrane hydrophone² is now the accepted “gold-standard” world-wide device for making absolute, traceable measurements of acoustic pressure distribution in medical ultrasonic fields. A number of designs of such devices exist, but broadly, they comprise a large sheet of PVDF in the form of a thin film, with gold or chromium electrodes vacuum-deposited on the surface, stretched across an annular frame. Metal film leads are evaporated onto both sides of the membrane, and the small overlap region formed defines the active area of the device. The majority of developments for the GEC-Marconi hydrophones were carried out in the early 1980’s³. Figure 3.3 depicts a typical design, known as a coplanar-shielded hydrophone due to its fabrication from a single layer of PVDF film. Modern manufacturing techniques have recently produced prototype devices with active elements as small as 40 μm in diameter, with bandwidths up to 150 MHz.

The characteristic acoustic impedance of PVDF is well matched to that of water and therefore, provided the membrane is thin, such hydrophones have the advantage of causing minimal disturbance to the acoustic field, especially as the ultrasonic beam generally passes through the aperture of the supporting ring. Additionally, the frequency response of membrane devices is smooth in the megahertz frequency range, and importantly for the characterisation of acoustic waveforms measured to be described in Sections 4 and 5, extends above 50 MHz for some devices.

3.5 HYDROPHONE-AMPLIFIER COMBINATIONS

Transducer characterisation measurements were made using a variety of membrane hydrophones, providing a large database of reference data for comparison with pulse-echo methods. A range of pre-amplifiers of various specifications were used with the hydrophones, with a variety of gain levels and available bandwidths, to investigate the effect of these on output beam parameters. The hydrophone and amplifier combinations used are shown in Table 3.3.

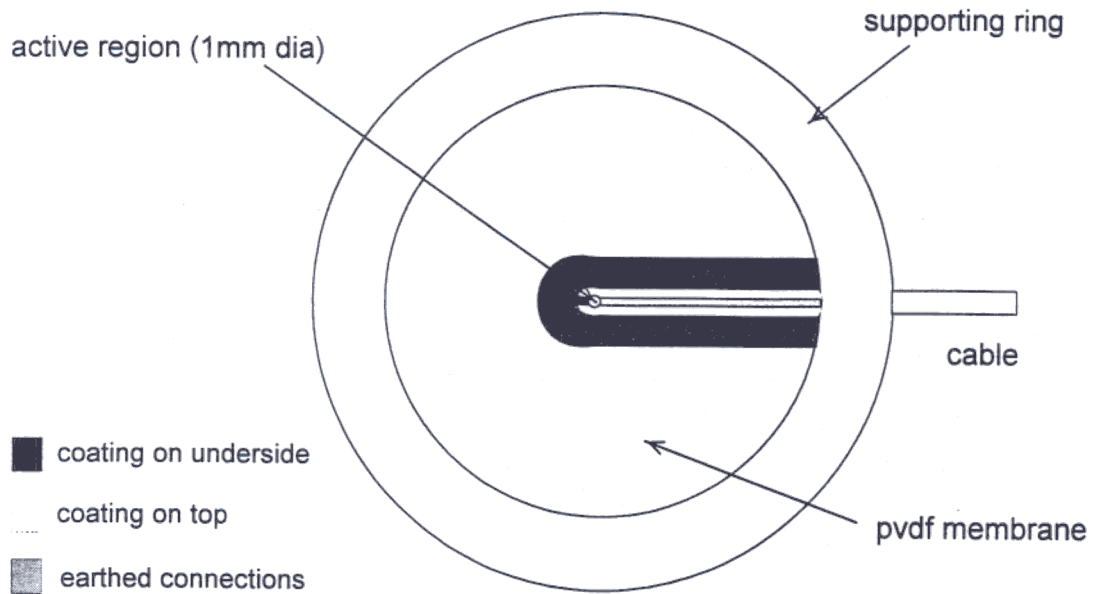


Figure 3.3: Schematic diagram of a coplanar-shielded membrane hydrophone

Table 3.3: Hydrophone and amplifier combinations used for beam profiling

Serial number of combination (hydrophone_amplifier)	Hydrophone type	Active element diameter (mm)	Combined -3 dB bandwidth (MHz)
3598016_556402	9 μm bilaminar	0.5	70
3598016_533911	9 μm bilaminar	0.5	40
3598016_55391001	9 μm bilaminar	0.5	70
3598016_56069	9 μm bilaminar	0.5	23
7603901_533911	9 μm coplanar	0.5	40
6526008_533911	9 μm bilaminar	0.2	40
6526010_533911	9 μm bilaminar	0.2	40
6526010_556402	9 μm bilaminar	0.2	70
7611026_533911	25 μm bilaminar	1.0	40

Additionally, a wide range of passive filters was available, with high pass devices of 200 kHz and 1 MHz used frequently during pulse-echo measurements to eliminate low frequency noise breakthrough. A range of experiments are described in Sections 6 and 7 that illustrate the effects of filtering on hydrophone and pulse-echo determined beam parameters.

PULSE-ECHO TARGET SPECIFICATIONS

Standards in this field are common in their recommendation of pulse-echo targets for beam profiling, and for the determination of the frequency response of transducers. Consequently, the targets used in the project may be divided into these two main areas.

3.6.1 Targets for frequency response assessment

Consultation of the existing Standards revealed a degree of flexibility in the specification of targets suitable for determining the pulse-echo frequency response of transducers. In all cases, however, the common requirement was that the target used should be flat, and in some cases (see Section 2), a tolerance on the surface finish was given. The specification of the target used is shown in Figure 3.4. The tolerance on the surface finish of the crown glass block was based on a factor of three better than the AS 1355 requirement of "63 microinches", which corresponds to $1.6\text{ }\mu\text{m}$. In some cases, requirements exist which stipulate the use of a planar reflector for on-axis profiling, and for this purpose, the glass reflector was also used.

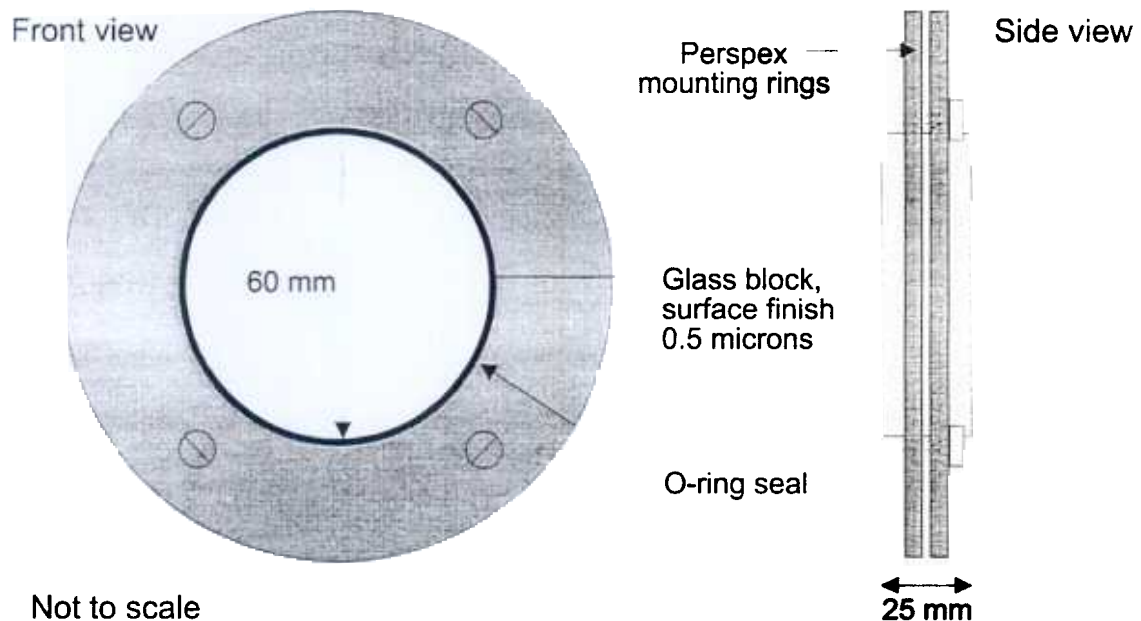


Figure 3.4: Schematic representation of planar pulse-echo target used for frequency response measurements

Point-like targets for beam profiling

Without exception, all of the current Standards in the field recommend the use of a ball pulse-echo target for making measurements of the beam profile across the beam axis, and some Standards also permit their use for axial profiling. It was decided that a range of such

targets would be designed and manufactured: these would correspond to the range of frequencies of transducers under investigation, and conform to the recommendations in the ASTM and the AS documents.

In addition, work completed recently at NPL on the testing of the performance of Doppler ultrasonic foetal monitors had shown that ball pulse-echo targets can exhibit significant structure in the strength of their response as a function of frequency⁴. These arise from interference effects caused by reflections from various parts of the target and mount. The authors advocated the use of flat-ended rods (planar disc reflectors) which produce a pulse-echo response which is much smoother as a function of frequency. They may also be easier to manufacture and mount. With this in mind, a variety of flat-ended rods were also produced, with a view to investigating their possible use in field characterisation.

3.6.2.1 Ball pulse-echo targets

Consultation with NPL Engineering Services led to a series of designs of ball targets, based around the central theme of having a stainless steel ball bearing mounted on a pedestal. Initial ideas included having a magnetised system, with the ball bearings interchangeable and located in a cup; however, this was unsuitable for the larger size targets, due to the side-on operating configuration when in the tank: the mass of a 10 mm diameter ball was such that it would not remain centralised in the cup. Additional problems included refining the pedestal design such that the diameter of the cup was sufficiently less than that of the ball bearing itself (whilst maintaining adhesion between the ball and the mount), so that any spurious ultrasonic signals produced by surface waves travelling over the ball, reflecting from the mount and then back again could be observed in a time-domain oscilloscope trace.

The final designs for 4 ball sizes are displayed in Figure 3.5. In all cases, it was decided to attach the ball bearings to the pedestals using adhesive. During the design process, it was discovered that a range of commercially-available styli normally used in dial test gauges would also be suitable for use as pulse-echo targets. Pulse-echo target diameters of 0.76 mm and 1.5 mm were realised in this way.

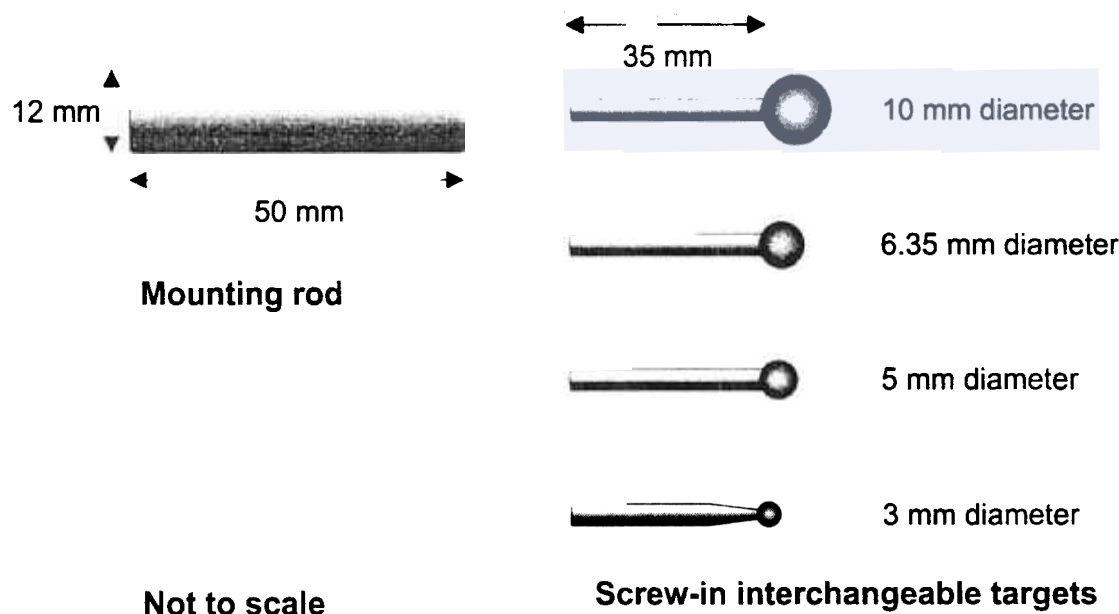


Figure 3.5: Schematic representation of ball pulse-echo targets used

3.6.2.2 Disc pulse-echo targets (flat-ended rods)

Clearly, the design of suitable planar pulse-echo target configurations is easier than that of spherical devices, primarily as the rods may be made long enough to gate out (in time) any spurious reflections. However, concerns over manufacturing tolerances may become more critical. Maintaining a circular end down to diameters less than 1 mm requires precision machining, and careful usage of the target. The diameters of the ends of the stainless steel rods used were 0.56 mm, 1.0 mm, 3 mm, 5 mm and 8 mm, with a tolerance of ± 0.05 mm. The surface finish was specified at ± 5 μ m. Figure 3.6 illustrates the target designs.

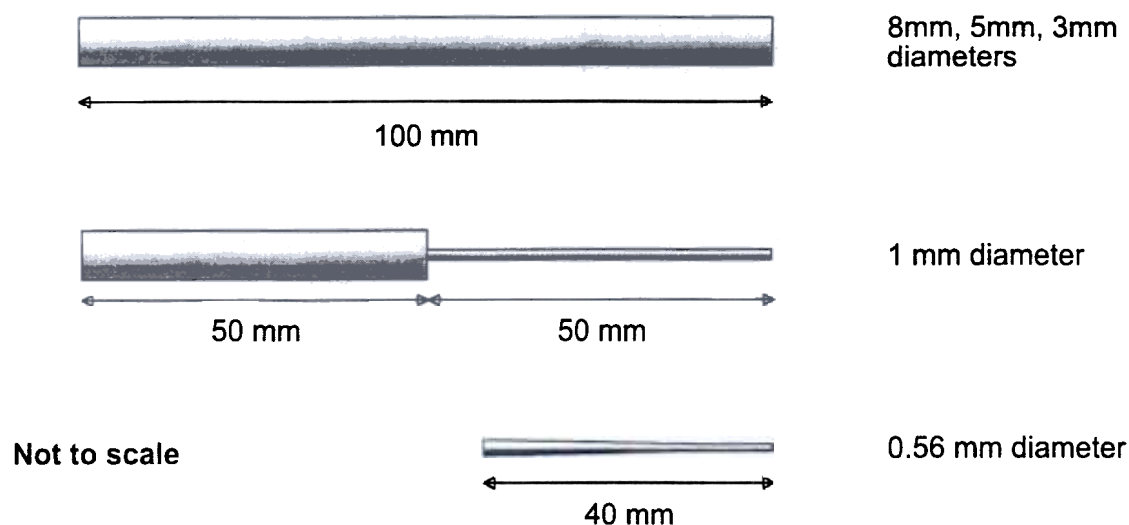


Figure 3.6 Specification of disc pulse-echo targets used

It should be noted that the rods were designed to be used in an end-on configuration, not side-on, a configuration which was discussed during the Industrial Advisory Group meetings, but which could not be used to provide information on beam symmetry, highlighted as being important in a number of Standards such as the McDonnell Douglas document, which could be interpreted in a simple way.

4 MEASUREMENT OF ACOUSTIC WAVEFORMS USING HYDROPHONES

4.1 BACKGROUND

This Section will consist predominantly of a series of figures representative of the acoustic waveforms determined using membrane hydrophones for the range of NDT systems studied. For the first time, these will establish that, at the frequencies used by commercially available NDT equipment, the acoustic pressures generated are sufficiently high to ensure that propagation from the transducer through the water medium must be considered as a nonlinear process.

4.2 RESULTS

A full analysis of the frequency measurements made during the project will be presented in Section 5; the purpose of this Section is to illustrate the time-domain waveforms acquired from a selection of the transducers measured and to provide data on σ_m , the shock parameter.

CMAM Meccasonics pulser-receiver

Figures 4.1 to 4.6 illustrate clearly the shocked nature of the acoustic pulse, and are typical examples of the waveforms measured and FFT's derived. The examples shown are of the 2.5 MHz focused, (F01951173), the 5 MHz focused, (F01951170) and the 10 MHz unfocused (F1658) respectively. The Meccasonics pulser is designed to operate with transducers of a wide range of frequencies, and consequently, the manner in which some transducers respond can reflect the wideband nature of the excitation. Figures 4.7 and 4.8 shows the effect of the drive signal (see Figure 3.1) on the 1 MHz focused transducer, F01951172. The acoustic waveform and FFT show that the transducer crystal is being excited in its 3rd and 5th order modes, in addition to the expected 1 MHz mode. Clearly, this produces an acoustic signal which is complex in character.

DERA-loaned flaw detector

Measurements made on the KB flaw detector are particularly useful for demonstrating the wide bandwidth of the hydrophone acquisition system, and the significant extent of nonlinear distortion in the propagation path. Figures 4.9 and 4.10 show a 10 MHz focused transducer (denoted "10F" elsewhere in this document), which produced very high values for the peak-pressure parameters at its focus. Additionally, this device was measured as having a beamwidth of 0.6 mm in its focal plane, which was at 34 mm from the output face. The measured centre frequency in this plane was 9.1 MHz. The FFT shows frequency components up to 90 MHz, exceeding the -3 dB bandwidth of the acquisition system.

CMMT Meccasonics system

The acoustic waveforms shown in Figures 4.11 and 4.12 were acquired from the 5 MHz unfocused transducer, F11941135, when connected to the CMMT Meccasonics system. A 0.5 mm coplanar membrane hydrophone was used, located at the Y_{0+} position. The measurement conditions were identical in each case: the only difference between the two traces is in the drive level setting on the Meccasonics pulser. The expected difference in acoustic pressure levels can be seen clearly, and the different pulse shape is attributable to the difference in frequency content of the two drive waveforms (see Figures 3.1 and 3.2).

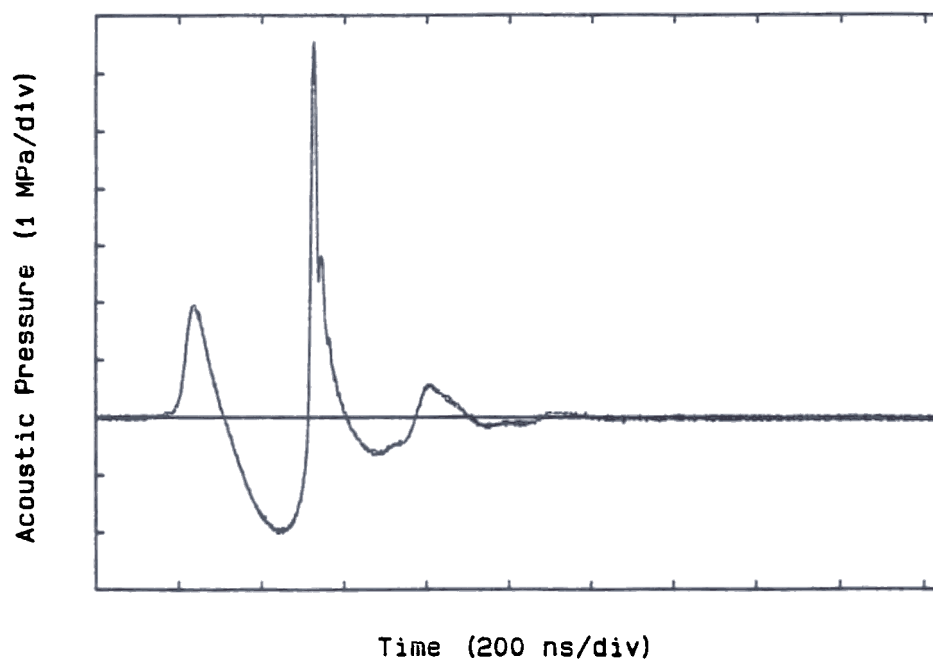


Figure 4.1: Acoustic waveform measured from Meccasonics 2.5 MHz focused transducer, F01951173, at focus (50 mm)

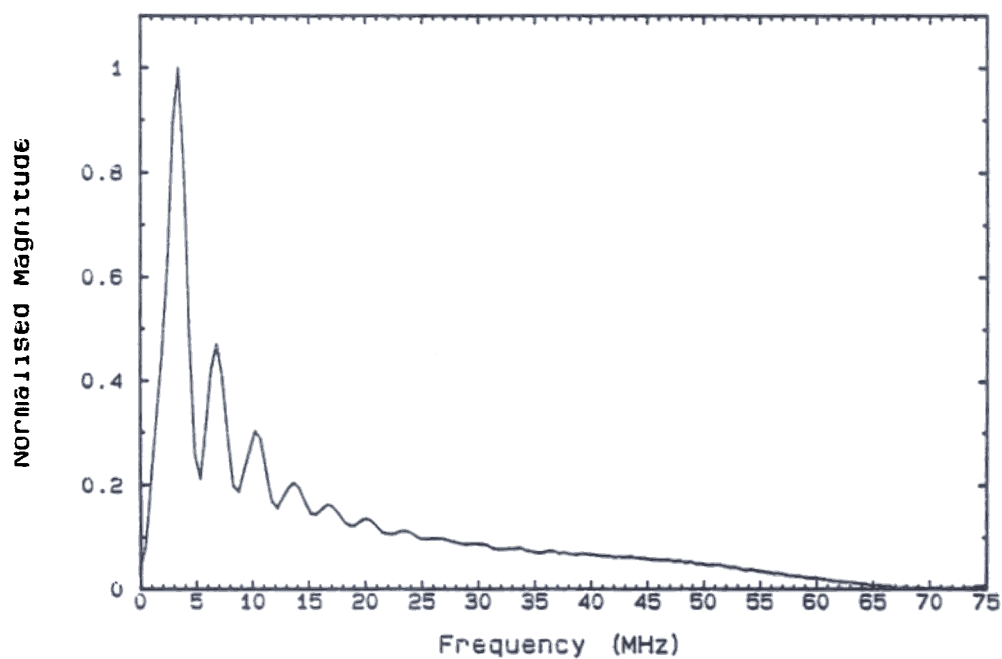


Figure 4.2: FFT of acoustic waveform measured from Meccasonics 2.5 MHz focused transducer, F01951173, at focus (50 mm)

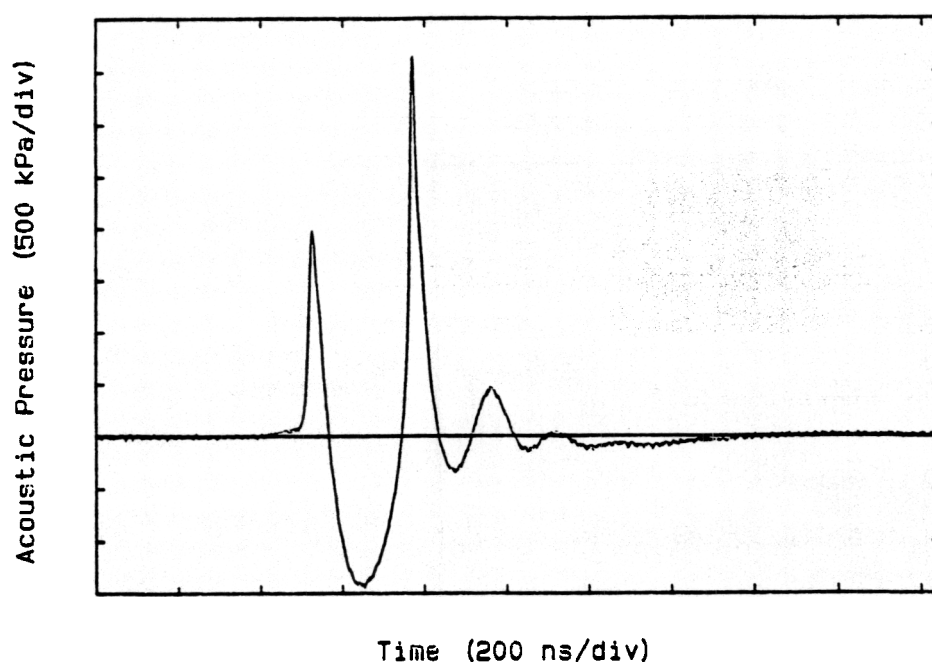


Figure 4.3: Acoustic waveform measured from Meccasonics 5 MHz focused transducer, F01951170, at focus (41 mm)

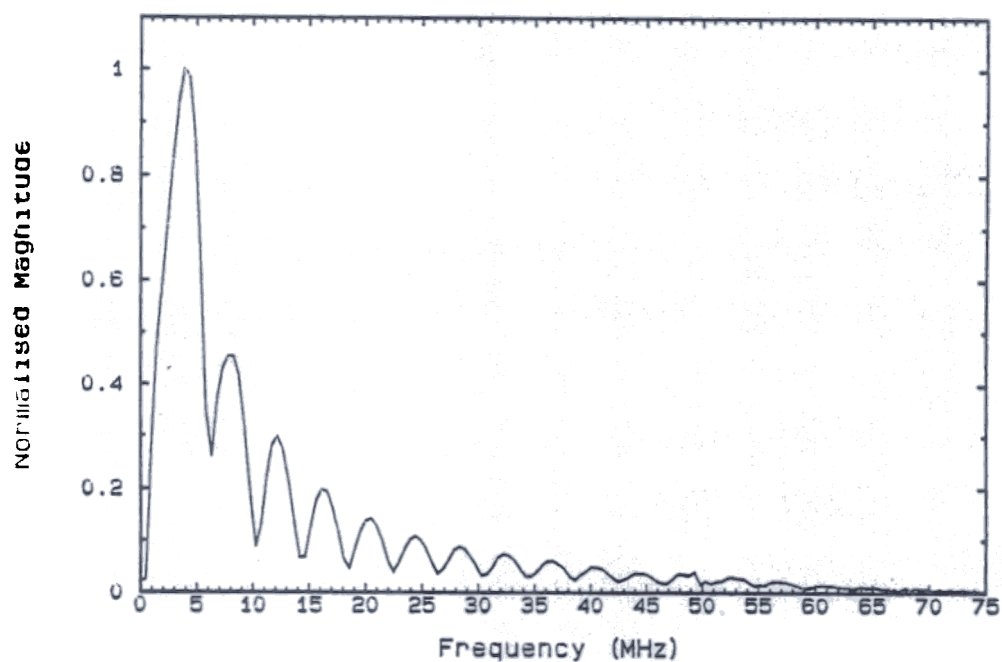


Figure 4.4: FFT of acoustic waveform measured from Meccasonics 5 MHz focused transducer, F01951170, at focus (41 mm)

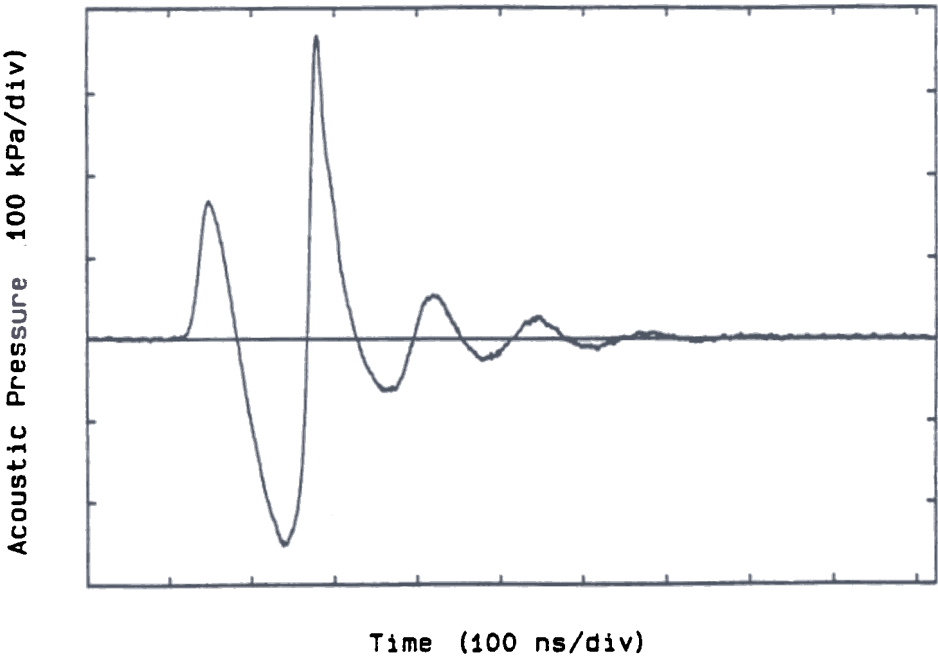


Figure 4.5: Acoustic waveform measured from Meccasonics 10 MHz unfocused transducer, F1658, at Y_0^+ (140 mm)

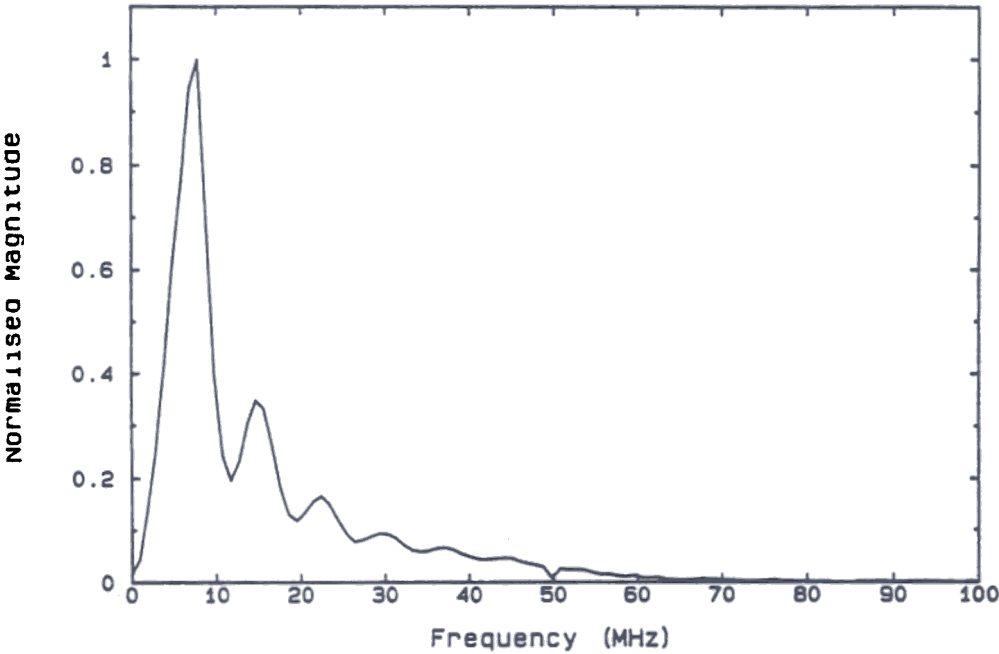


Figure 4.6: FFT of acoustic waveform measured from Meccasonics 10 MHz unfocused transducer, F1658, at Y_0^+ (140 mm)

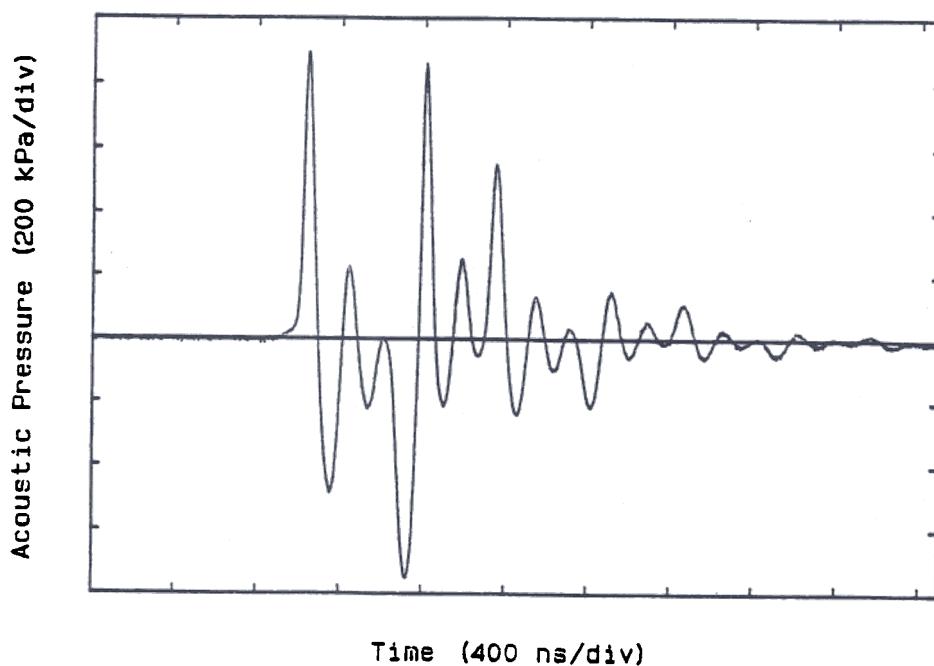


Figure 4.7: Acoustic waveform measured from Meccasonics 1 MHz focused transducer, F01951172, at focus (54 mm)

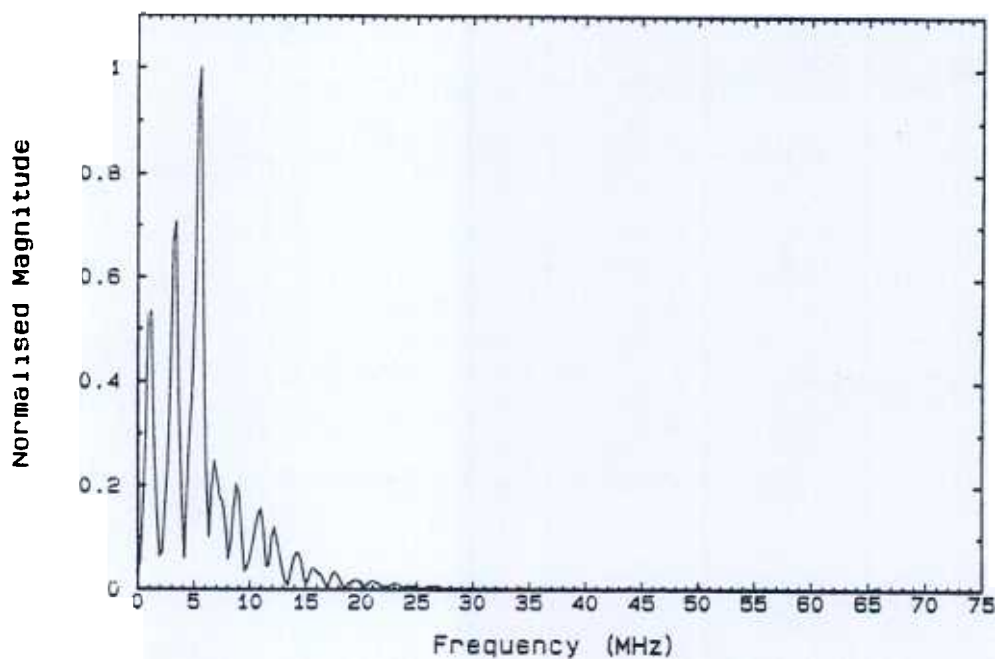


Figure 4.8: FFT of acoustic waveform measured from Meccasonics 1 MHz focused transducer, F01951172, at focus (54 mm)

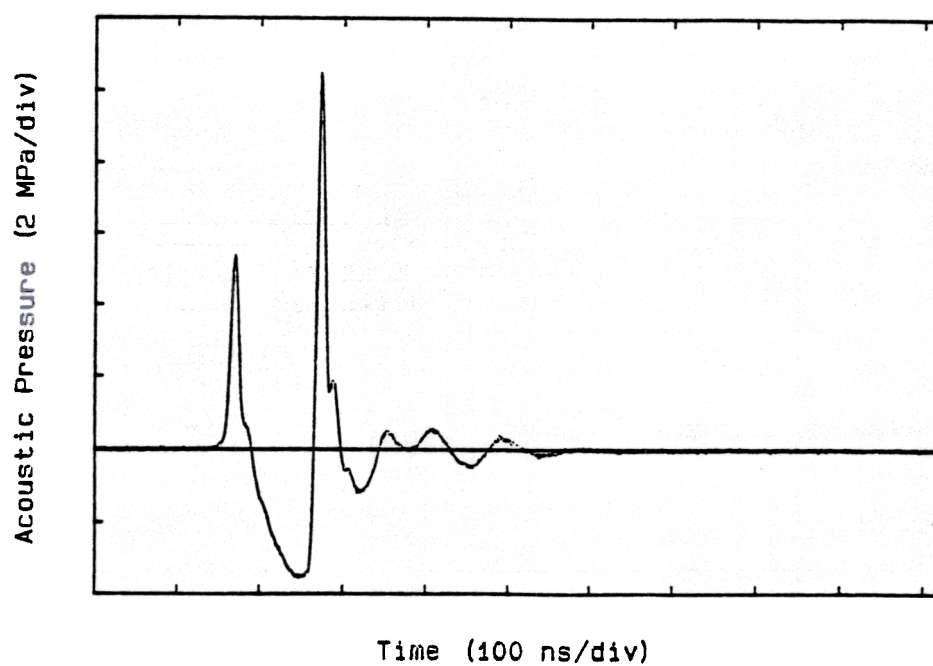


Figure 4.9: Acoustic waveform measured from DERA 10 MHz focused transducer "10F" at focus, 34 mm

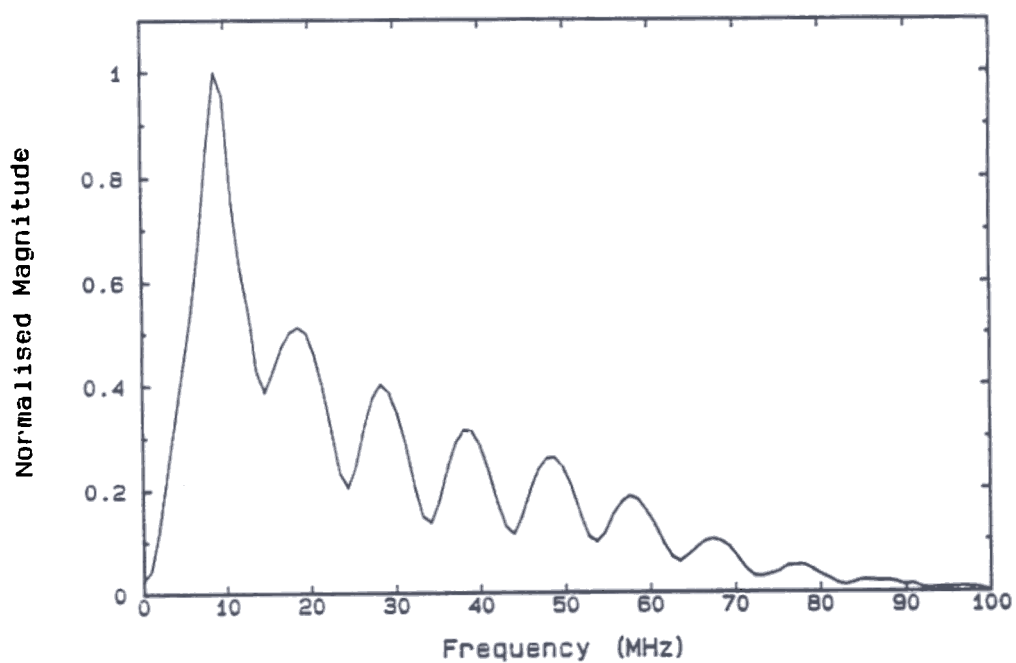


Figure 4.10: FFT of acoustic waveform measured from DERA 10 MHz focused transducer "10F", at focus, 34 mm

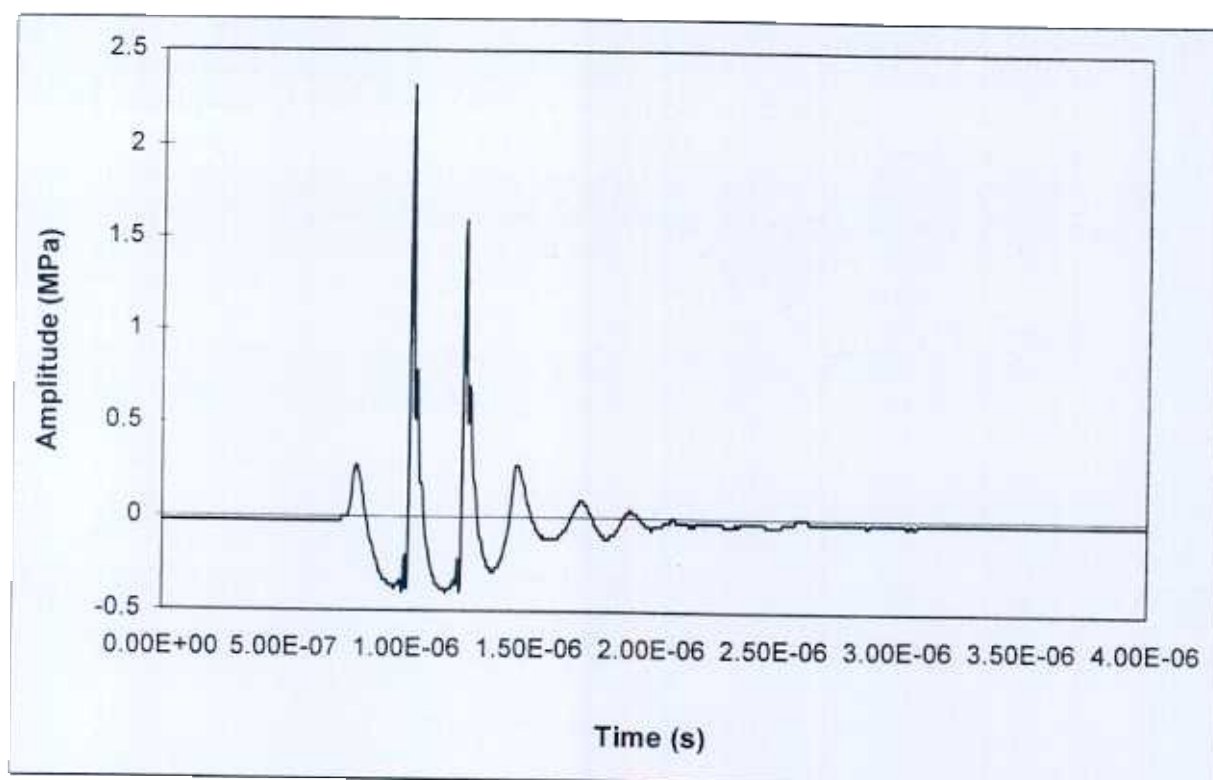


Figure 4.11: Waveform acquired at Y_{0+} of Meccasonics 5 MHz unfocused transducer, (F11941135), connected to NPL/CMMT C-scan system, low frequency drive setting, using hydrophone-amplifier combination IP014_533911

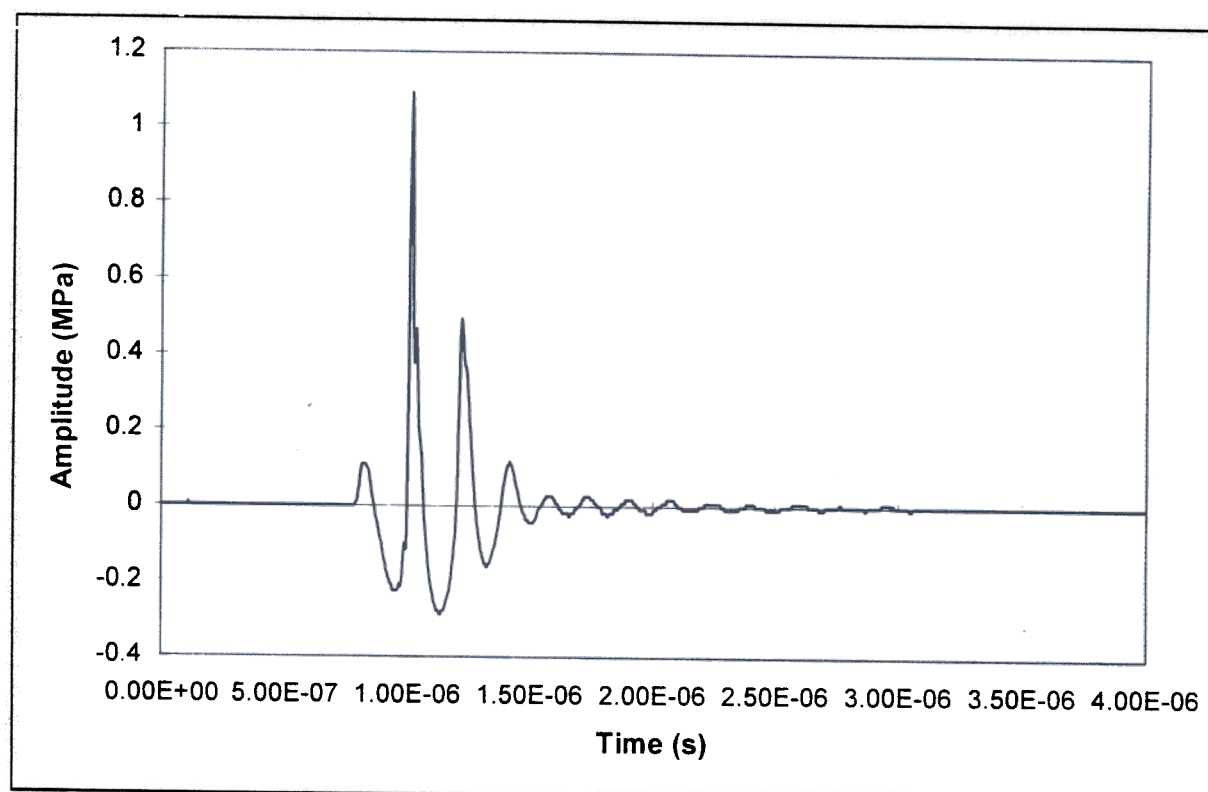


Figure 4.12: Waveform acquired at Y_{0+} of Meccasonics 5 MHz unfocused transducer, (F11941135), connected to NPL/CMMT C-scan system, high frequency drive setting, using hydrophone-amplifier combination IP014_533911

4.3 NONLINEAR PROPAGATION AND DISTORTED ACOUSTIC WAVEFORMS

An in-depth treatment of nonlinear propagation clearly lies beyond the scope of the current report. The interested reader is referred to one of a number of texts dealing with nonlinear acoustics such as Beyer and Letcher⁵. The distortion arises because the propagation speed of ultrasound is pressure dependent so that during propagation, the compressional half cycle travels faster than the rarefactive half-cycle. As the pulse propagates away from the source, the waveform will undergo a cumulative distortion, with the compressional half cycle attempting to 'catch up' with the rarefactive half-cycle. It can never actually do this: the closest it comes is to generate the shock seen in the acoustic waveform which has an infinitesimal rise-time.

The importance of this phenomenon to the current C-scan study is two-fold. Firstly, energy is being pumped from the fundamental driving frequency into higher harmonics which are absorbed more readily. For the band-limited pulse-echo measurement of attenuation, this means that the fundamental frequency component is attenuated at a much greater rate than expected from normal linear considerations (with orders of magnitude difference). In situations where the absolute attenuation of the specimen is important, for example in attempting to derive an intrinsic property of the material under test, this effect can lead to large uncertainties in the derived attenuation coefficient. This aspect is specifically dealt with in Section 10 of this report. Additionally, when a system is operating in a nonlinear regime, further increases in the electrical drive to the transducer will result in minimal increases in the pulse-echo signal level of the fundamental frequency component. The system is said to have reached saturation.

The second area of interest lies in the effect that nonlinear propagation, and in particular the resultant distortion of the resultant acoustic waveform, has on measurements of the transducer field properties. In this respect, there are a number of characteristics of nonlinear acoustic waveforms, as determined using wide-bandwidth hydrophones, which are relevant. These are summarised below:-

- the waveforms are strongly asymmetric, with the peak-positive acoustic pressure (p_+) exceeding the peak-negative acoustic pressure (p_-) by a factor of 3 or more. The determination of the acoustic parameters such as Y_{0+} and beamwidths in specified planes will depend on the particular parameter measured. Typically, p_+ and p_- will attain their maximum values at different positions along the acoustic axis. Within the field of medical ultrasonics, it has become accepted that measuring a quantity called the pulse-pressure squared integral ($ppsi$), related to the energy in the pulse, is more reliable as it is the least affected by nonlinear propagation. The relationship between the various quantities for a typical acoustic waveform is given in Appendix D;
- the nonlinear acoustic waveform measured is a shock-wave, characterised by a rise-time of a few nanoseconds. Viewed in the frequency domain, the acoustic waveform contains a number of high frequency components which are multiples of the fundamental frequency. Use of a wideband measurement system is therefore essential for determining the true acoustic waveform but determination of the parameters can be crucially dependent on the properties of the receive system⁶;

the extent of waveform distortion may be formally quantified through a parameter σ_m known as the nonlinear propagation parameter, where the subscript m signifies that the value of σ has been determined from measured parameters as outlined in Appendix D. Crudely, only in situations when $\sigma_m < 0.5$ can propagation be considered a linear process.

4.3.1 Calculations of the shock parameter, σ_m

Table 4.1 gives a compilation of shock parameter calculations for a range of systems measured during this study. From the table, it can be seen that the σ_m values are derived predominantly from focused transducer measurements: unfocused devices do not often have sufficiently high focal gain values (proportional to ratio of focal (or Y_{0+}) beam area to crystal area). It is considered that normally, σ_m values of greater than 1.5 or more represent shocked waveforms: for the severest case, the DERA "10F" transducer yields a σ_m of over 4.

Table 4.1: Calculated σ_m values for transducers measured

Transducer serial no	Type	σ_m
F01951172	1 MHz focused	0.16
F01951173	2.5 MHz focused	2.8
F01951170	5 MHz focused	2.5
F11941135	5 MHz unfocused	3.85
F10941099	10 MHz focused	2.53
001401	10 MHz focused	3.68
"10F"	10 MHz focused	4.50

4.4 SUMMARY

From the results presented it is clear that nonlinear acoustic propagation from commercial NDT systems occurs, arising due to the elevated acoustic pressures generated which can be as high as 10 MPa. Whereas its occurrence in the field of medical ultrasound has now been accepted, the phenomenon has not yet been documented in the field of NDT. This is undoubtedly due to the restricted measurement bandwidths of C-scan systems, which essentially detect only the fundamental component generated by the transducer, which is effectively band-pass filtered from the broadband signal.

5 FREQUENCY RESPONSE DETERMINATION

This Section describes the experimental work performed during the project in investigating the methods used to determine the frequency response of a transducer. It also contains an overview of the problems posed by frequency downshift and illustrates the significant effect that the drive unit employed can have on the frequency data obtained.

5.1 BACKGROUND

The measurement of the frequency response of transducers used in NDT is specified in all Standards in this area, even within those that do not require the assessment of any spatial parameters of the ultrasonic beam, and hence can be regarded as one of the most important quantities. Determination of the frequency response provides information on the suitability of the transducer for the scanning of particular structures (for example, lower frequency transducers are essential for the C-scanning of honeycomb materials), and also dictates to a large extent the spatial resolution available from the transducer. The procedures and requirements on targets contained within the Standards summarised in Section 2 were used as the basis for the pulse-echo measurements made: the use of hydrophones in measuring frequency parameters is without precedent in the NDT transducer arena. The work of Preston and Bond⁴ described in Section 3.6.2 has shown that ball pulse-echo targets exhibit significant structure in their target strength response as a function of frequency. For this reason, ball targets were not used in the frequency response investigations.

5.2 FREQUENCY DOWNSHIFT

The measurement of the frequency response of transducers operating at high frequencies (those above 7.5 MHz) can pose significant problems. The origin of these difficulties is frequency downshift. At low megahertz frequencies, the attenuation of ultrasound in water is small, certainly in comparison to transmission losses seen in carbon fibre, for example, and in the calculation of attenuation coefficient data, is usually corrected for via the application of a simple factor. However, at higher frequencies, the signal attenuation in the water path becomes more significant, as the attenuation coefficient of water increases as the square of the frequency. The net effect of this, for a broadband pulse containing a range of frequency components, is to produce a downshift of the measured centre frequency. Transducers of wide bandwidths will be more susceptible to such effects, as the elevated frequency components in the transmitted signal will be attenuated at a higher rate. Any downshift may also shorten the measured focal length of focused transducers.

Frequency downshift was investigated only to a limited extent, although as the range of transducers used in the project was limited from 0.5 - 10 MHz (defined by the scope of the Part 2: Calibration Procedure), it was considered that the effect would be of minor concern. Generally, the recommendations on measurement positions in the Standards for unfocused transducers state that the transducer-pulse-echo target separation should be set at 50 mm, whereas focused transducers should be positioned such that the echo signal is maximised. This means that frequency downshift is likely to be more acute in the case of focused transducers with a long focal length. A sample of the guidelines on water path lengths provided in ASTM E 1065-92 is reproduced in Figure 5.1.

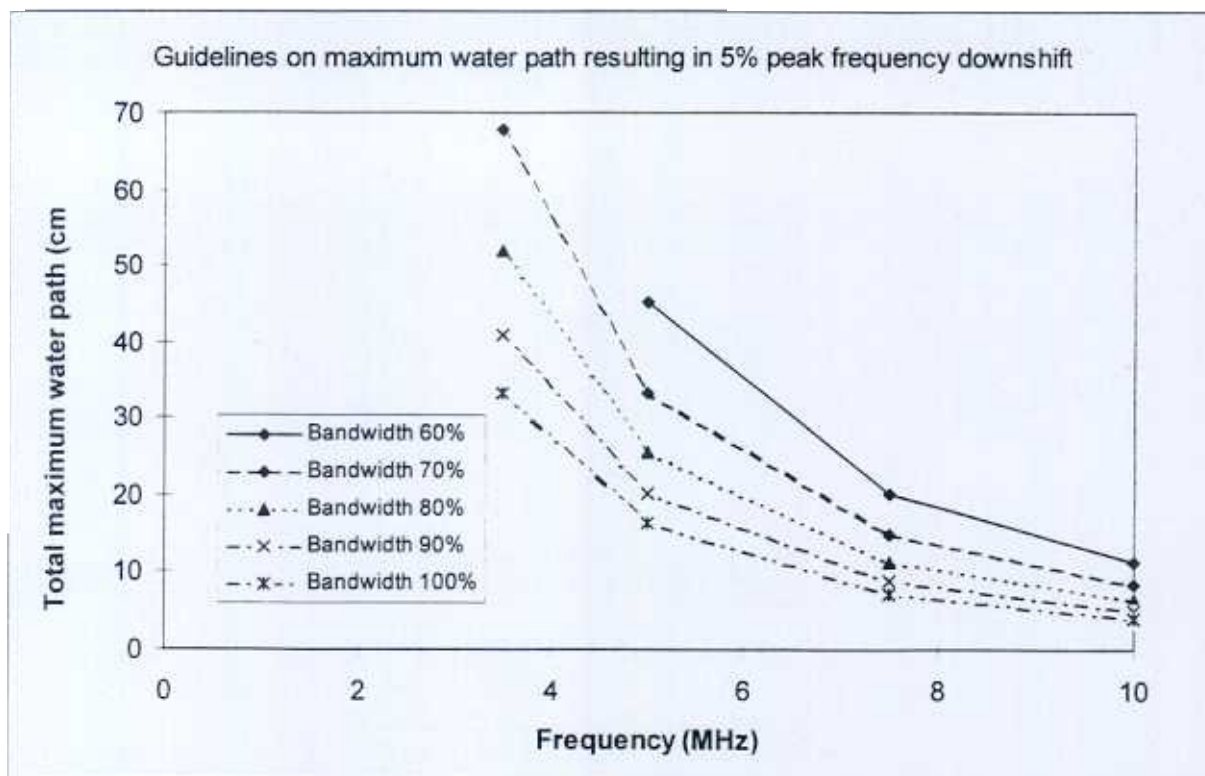


Figure 5.1: Sample data for maximum water paths permissible to minimise peak frequency downshift as a function of nominal frequency, for five bandwidth cases

At 10 MHz, if we consider a transducer with a measured -6 dB pulse-echo bandwidth of 70%, it can be seen from Figure 5.1 that a maximum water path of around 10 cm should be used to limit the extent of frequency downshift to 5%. For a typical 50 mm focused device, pulse-echo measurements made at the focus would be right on this limit although, due to the single propagation path, hydrophone measurements would be comfortably within it.

Table 5.1 gives an example of the downshift observed for the measurements made using a hydrophone for the extreme conditions provided by the 10 MHz focused transducer (F10941099). The frequency data for F10941099 illustrates a change in the -3 dB centre frequency when moving the hydrophone from the face of the transducer to the focal position from 10.8 MHz to 10.3 MHz i.e. less than 5%.

5.3 HYDROPHONE MEASUREMENTS

5.3.1 General

The measurement of the frequency response of the transducers used was performed as an integral part of the transducer characterisation process. After the system had been aligned (the method for which will be described in Section 6.2), an axial scan was performed to determine the position of the focal point or Y_{0+} in *ppsi*, the hydrophone was moved to this position, and then across the axis in fine increments (25 μm) to ascertain the exact position of the maximum signal, measured in terms of the oscilloscope V_{rms} . At this position, the acoustic waveform was then digitised and stored. Fourier analysis of the data produced the spectral characteristics of the waveform, and in each case, values for the centre frequency, peak frequency and frequency bandwidth (at the -3 dB level) were obtained. The -3 dB level is used for hydrophone measurements as it is less influenced by the presence of nonlinear

distortion in the propagation path (see Section 4.3): which will serve to produce higher frequency components in the Fourier Transform of the received pulse. This procedure was carried out for each of the transducers used, and the frequency data produced can be found in Table 5.1.

Table 5.1: Summary of frequency-domain data for Meccasonics transducers derived using a hydrophone

Transducer serial number	Axial position (mm)	Nominal frequency (MHz)	Peak frequency (MHz)	-3 dB centre frequency (MHz)	-3 dB bandwidth	Notes
F1657 (unfocused)	42	1	1.16	1.14	32%	
F1655 (unfocused)	38	2.5	2.70	2.43	76%	
F11941135 (unfocused)	59	5	4.81	4.72	37%	
F1658 (unfocused)	140	10	7.77	7.1	45%	
F01951172 (focused)	54	1	5.60	5.5	8%	Avg. from two measurement systems
F01951173 (focused)	50	2.5	3.33	3.31	39%	
F01951170 (focused)	41	5	3.9	3.81	74%	
F10941099 (focused)	52	10	8.7	10.3	65%	
F10941099 (focused)	4.9	10	7.5	10.8	96%	

5.3.2 Special case

The result that stands out as being exceptional is the 1 MHz focused transducer, F01951172, where the measured -3 dB centre frequency was actually 5.5 MHz. Examination of the time domain and frequency domain data obtained (Figures 4.7 and 4.8 respectively) shows that this is attributable to the drive characteristics of the Meccasonics pulser-receiver used during the project. The lower frequency setting on the pulser produced an excitation pulse that may be seen in Figure 3.1. This caused the focused 1 MHz transducer crystal to be excited at its 3rd and 5th order harmonics as well as at the fundamental, producing frequency spectra that were extremely dependent on measurement position. Waveforms acquired at the focus of F01951172 determined using a wide-bandwidth system were actually dominated by the 5th order component. Figure 5.2 shows the variation in the relative magnitudes of the 1st, 3rd and 5th order components as a function of position. Compare this to the data found for the same transducer when measured using a band-limited pulse-echo technique (see Table 5.2).

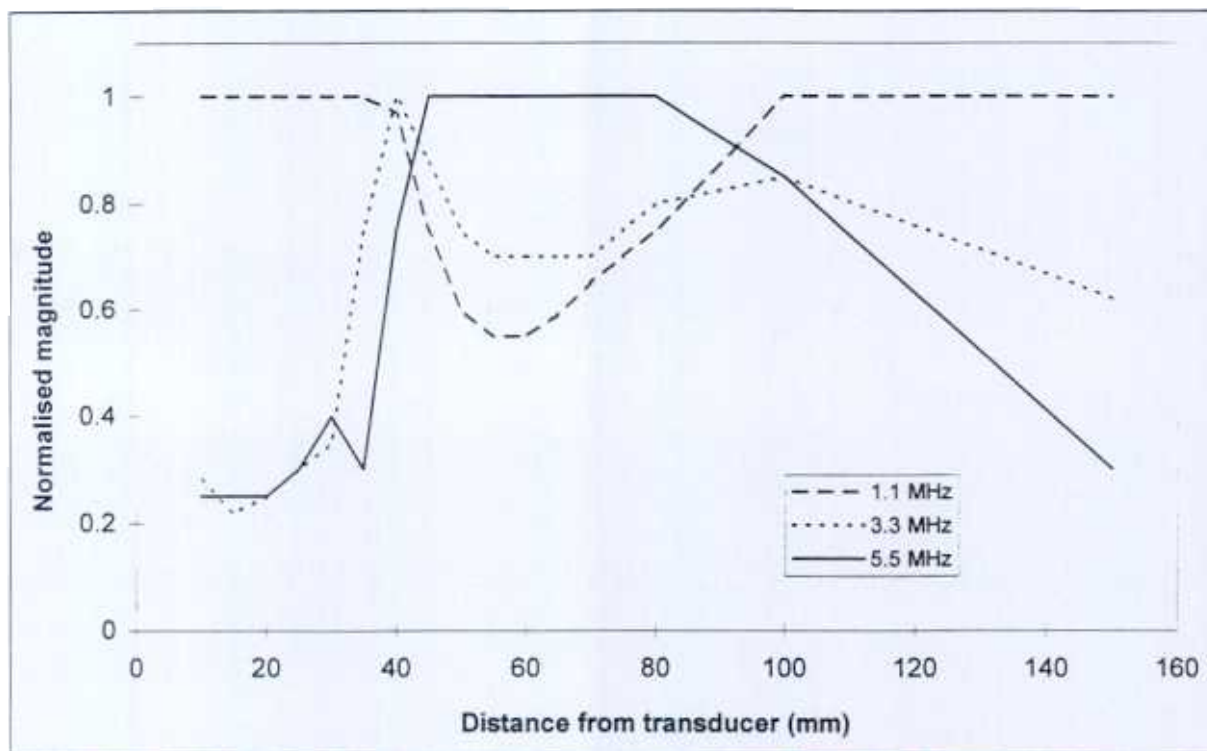


Figure 5.2: Normalised frequency magnitudes as a function of position for F01951172

As would be expected, the 1.1 MHz component dominates the frequency response close to the transducer, with the 3.3 MHz and 5.5 MHz components building up in level as the separation is increased. The nominal focus of the transducer was 50 mm, and at this position the nominal fundamental is close to its lowest magnitude. At distances greater than 100 mm, it is likely that the preferentially higher attenuation of the 5.5 MHz and 3.3 MHz components causes them to die away, and so the 1.1 MHz component dominates again. Such a response in a transducer means that wide bandwidth hydrophone measurements may be difficult to interpret.

5.4 PULSE-ECHO MEASUREMENTS

As with the hydrophone measurements, the pulse-echo frequency response of transducers was carried out as part of the overall characterisation process, and so the data available was generally acquired at the Y_0+ position or the focal distance, Y_F , for focused transducers. Measurements were performed using the planar, and disc pulse-echo targets described in Section 3.6, and the results obtained are presented in Table 5.2. In line with the Standards reviewed in Section 2, the frequency parameters are quoted at the -6 dB level. The rationale behind performing measurements using a range of disc pulse-echo target diameters was to see if accurate frequency data could be obtained using small diameter devices: these could then be specified for use as overall transducer characterisation tools for both frequency response and spatial parameter determination.

Table 5-2: Summary of frequency-domain data for Meccasonics transducers derived using pulse-echo techniques

Transducer serial number	Axial position (mm)	Nominal frequency (MHz)	Peak frequency (MHz)	-6 dB centre frequency (MHz)	-6 dB bandwidth	Notes
F1657 (unfocused)	42	1	1.07	1.13	37%	1 mm rod
F1657 (unfocused)	42	1	1.06	1.13	39%	0.56 mm rod
F11941135 (unfocused)	60	5	4.82	4.72	38%	1 mm rod
F11941135 (unfocused)	60	5	4.86	4.64	42%	5 mm rod
F11941135 (unfocused)	60	5	5.08	4.84	32%	8 mm rod
F11941135 (unfocused)	60	5	5.10	4.82	33%	glass
F01951172 (focused)	40	1	1.07	0.98	52%	glass
F01951173 (focused)	11	2.5	2.89	2.24	115%	glass†
F01951170 (focused)	41	5	1.43	2.72	143%	glass

† target tilted to minimise edge wave component

Although data is available for only a limited number of devices, there are still some interesting points of note. In particular, the range of measurements made on the 5 MHz unfocused transducer (F11941135) indicate a weak trend as a function of target size, with the peak frequency increasing from 4.82 MHz to 5.10 MHz as the pulse-echo target increases to effectively an infinite reflector. This is a relatively small variation and arises due to the frequency dependent scattering of the disc target used.

The data quoted for the focused 2.5 MHz transducer was obtained by tilting the glass target used about its vertical axis. This can be used to minimise the edge-wave component (see Appendix C), as it destroys the coherence of its reflection from the glass back to the transducer. The remaining part of the pulse is then attributable only to the plane-wave, and as a result, the absence of interference from the edge-wave produces a relatively clean FFT, yielding the results shown in the Table. This approach requires further validation for it to become a recommended procedure suitable principally for high frequency, long focus transducers.

5.5 SUMMARY

In general, it is not possible to directly compare frequency response measurements derived using hydrophones with those obtained using the reflections from small targets. The former is used to measure the true acoustic waveform at the particular position in the field. In contrast, the pulse-echo determination depends on the frequency-dependent scattering from the small target used as well as the receive bandwidth of the electronic processing. Although only a

limited number of measurements have been completed in the frequency response investigations, a number of conclusions may be drawn:

- the upper frequency limit of 10 MHz for the transducers characterised has meant that the effects of frequency downshift have been minimal (in most cases being <5%). However, the high frequency focused transducers used only just fall within the ASTM guidelines;
- the use of small disc pulse-echo targets for determining frequency response has provided good agreement with large planar targets, so such targets could potentially be used for determination of frequency response and for spatial parameter determination;
- hydrophone measurements on the 1 MHz focused transducer have shown that the wideband excitation signal of the drive unit can cause a transducer to be driven at several frequencies simultaneously, producing widely varying frequency-domain results as a function of position for wide-bandwidth hydrophone-derived measurements.

5.6 RECOMMENDATIONS

Hydrophone-based frequency response measurements on focused transducers should be made at the focus, Y_F , subject to falling within the guidelines in ASTM regarding frequency downshift. Similarly, pulse-echo measurements, which may be undertaken using disc or planar targets, should be performed at the position of maximum response.

Hydrophone-based frequency response measurements on unfocused transducers should be made at the nominal Y_{0+} position, subject to falling within the guidelines in the ASTM regarding frequency downshift. Pulse-echo measurements, which may be performed using disc or planar targets, should be carried out at a separation from the transducer of 40 mm or less.

6 MEASUREMENTS OF AXIAL BEAM PROFILES

This Section describes the determination of the spatial characteristics of the ultrasonic transducer field along the transducer beam-alignment or acoustic axis. During the study, measurements were made using both hydrophones and small pulse-echo targets; differences in implementing the techniques and the results obtained will be discussed in detail.

6.1 BACKGROUND

Measurement of the axial beam profile of acoustic pressure is one of the most crucial aspects of transducer characterisation. All Standards reported in Section 2 recommend the use of pulse-echo targets for axial profiling measurements although ASTM E 1065-92 additionally permits the use of piezoelectric hydrophones. The relationship between these two fundamentally different methods of measurement formed one of the primary study areas underpinning the material presented in this Section.

6.2 GENERAL EXPERIMENTAL SETUP PROCEDURE

A well defined protocol was established for beam-plotting measurements, predominantly for the purposes of system alignment, which is crucial in the determination of the axial beam profile. Some of the details will be described in this sub-Section: the procedures were designed to ensure that the mechanical axis of translation of the beam-plotting tank was coaxial with the acoustic axis of the transducer.

The trigger output from the pulser was used to trigger the oscilloscope with the separation distance between the transducer and hydrophone or pulse-echo target being derived from the time-delay between the electrical drive signal and the received acoustic pulse, and the sound propagation velocity of the water in the test tank.

6.2.1 Hydrophone measurements

Alignment involved carrying out the following iterative procedure involving two measurement planes. In the case of focused transducers, the hydrophone was moved to a separation of approximately 10 mm greater than the nominal focus; for unfocused transducers, the separation was set at the nominal Y_{0+} , plus 10 mm. The delayed time-base on the oscilloscope was set up as required, according to the sound velocity and separation (Y direction). In this first measurement plane, the observed positive voltage on the oscilloscope display was maximised by using the cross-axial adjusters on the hydrophone mount, in both X and Z directions.

The separation distance was then adjusted to approximately twice that of the nominal focus or Y_{0+} , and in this second measurement plane, the positive voltage on the oscilloscope was again maximised, this time by using the angular and tilt adjusters on the transducer mount. The transducer or hydrophone was then returned to its original separation (first measurement plane) where the signal maximisation procedure as described above was repeated. Through repeated maximising iterations at these two measurement planes, the system was deemed to be aligned when the peak-positive voltage in each of the planes was within 3% of the maximum in that plane. This alignment procedure was carried out each time the transducer, pulse-echo target or hydrophone was changed.

Pulse-echo measurements

In the ball pulse-echo target case, similar alignment procedures were followed, using near and far separation planes defined as in the hydrophone case. For the disc pulse-echo targets, an additional set of adjustments were made close to the output face of the transducer, maximising the observed oscilloscope signal as a function of the angular variation of the pulse-echo target mount. Finally, for measurements made using the planar pulse-echo target (glass reflector), the lateral position of the target was adjusted by eye (at the first measurement plane), such that the beam axis, assumed to be coincident with the geometrical centre of the transducer output face, would strike the target approximately at its centre. The observed pulse-echo signal was then maximised using angular adjustments on the target mount. The second alignment plane was then used to check the angular maximisation of the transducer.

6.3 MEASUREMENT PROTOCOL

Measurements of the axial variation in acoustic pressure of unfocused transducers, undertaken to establish the position of Y_{0+} , are required by the majority of the Standards described in Section 2, even though during actual C-scan operation the Y_{0+} position is not necessarily used as the stand-off distance between the transducer and the sample under test or reflector plate. In some instances the reasons for this are practical, as in the case of a 10 mm unfocused 10 MHz transducer for example, the predicted position of Y_{0+} is approximately 170 mm. A total water path of 340 mm for a transducer operating at 10 MHz would produce a significant downshift in the observed acoustic working frequency, a problem discussed in ASTM E 1065-92, and described in detail in Section 5.2.

Perhaps of more importance is the measurement of the axial response of focused transducers, providing data which enables the focal position and the focal zone (focal depth) to be determined. The accurate characterisation of these transducers is important for their use in C-scanning, as these parameters may be used to define the set-up conditions.

Hydrophone measurements

The ASTM and Panametrics documents (Section 2) allow the use of hydrophones in axial profiling. Using the NPL Beam-Plotting Facility described in Section 3.1, a variety of hydrophone-amplifier combinations were used to investigate the distribution of acoustic pressure in the ultrasonic field produced by the transducers. As has been seen previously (Section 4), the fields generated by the majority of the drive unit-transducer combinations investigated exhibit a significant degree of nonlinear distortion. Some of the focused transducers measured produced acoustic pressures of up to 10 MPa, with harmonic frequency components up to 100 MHz. Some hydrophone measurements were therefore additionally carried out with passive filters applied to the signal chain to investigate the effect of restricting the bandwidth.

After the system had been aligned as required in each case, the separation distance between the transducer and the hydrophone was set at typically 20 mm, with the transducer then being scanned incrementally away from the hydrophone along the acoustic axis in 0.5 mm steps. At each position, the software control system acquired and stored the maximum and minimum pulse voltages read from the oscilloscope, in addition to the pulse energy. The scan was truncated at a position where the observed positive voltage level was 10% of the maximum voltage.

Pulse-echo measurements

In all Standards, pulse-echo techniques are recommended to assess the axial characteristics of the fields produced by both focused and unfocused transducers. These techniques can be implemented in the form of extended flat reflectors as well as ball targets, as it is considered by some Standards that aligning a ball target along the acoustic axis can be a difficult procedure. In these cases, performing an axial plot *per se* is not mandatory: instead, it is permissible to carry out a series of cross-axial scans at a variety of axial separations, and interpolate through the maximum values in these scans to produce an axial plot. Consequently, the glass target described in Section 3.6.1 for use in the determination of frequency response was also employed for the purposes of axial scanning. The ball and disc pulse-echo targets described in Sections 3.6.2.1 and 3.6.2.2 respectively were additionally used. A similar measurement procedure to that used for hydrophone scanning was carried out for pulse-echo measurements. The narrow-band nature of the pulse-echo technique meant that in comparison to the hydrophone case, the range of positions over which the on-axis maxima occurred according to the parameter chosen for evaluation was very small: often, the peak-positive, peak-negative and pulse energy maxima were coincident.

6.4 RESULTS

Unless stated otherwise, in this Section, for comparison reasons, the term “*ppsi*” will be used to refer to both the pulse pressure-squared integral determined using a hydrophone, and the pulse energy determined from pulse-echo techniques, even though in the latter case, it is not actually the acoustic pressure which is determined.

Unfocused transducers

6.4.1.1 Hydrophones and small targets

Table 6.1: Axial results obtained on 5 MHz unfocused transducer F11941135. All pulse-echo data acquired with 1 MHz high pass filter in place, hydrophone data unfiltered

Device	Position of Y_{0+} (mm)		
	$V_{\max}$	$V_{\min}$	Energy
0.2 mm hydrophone	60	53	59
0.5 mm hydrophone	65	52	60
1 mm disc	57	54	58
5 mm ball	52	49	52.5
0.76 mm ball	54	50	53.5

Comparison of values obtained for the different measurement devices in Table 6.1 shows that there is good agreement between the hydrophones and the disc pulse-echo target, particularly when the Y_{0+} maximum in energy is considered. Agreement between the hydrophone and the ball pulse-echo targets is not so good, although the largest difference, for the 5 mm ball, is still within 11% of the hydrophone value. Note also the significant difference in the Y_{0+} position for $V_{\min}$ compared to the other two parameters for the

hydrophone case. As described above in Section 4, the hydrophone-measured acoustic pulse exhibits asymmetry arising due to nonlinear distortion: in this case (considering the modulus), p_+ was a factor of 2.5 higher than p_- . In the calculation of $ppsi$, the p_+ component hence dominates, which explains the similarity between the Y_{0+} positions noted for p_+ and $ppsi$. Generally, the pulse-echo devices show a smaller variation in the three parameters, as expected, due to the limited measurement bandwidth. None of the hydrophone-derived results shown in Table 6.1 have been subjected to low pass signal filtering; when this is done the measured position of the last axial maximum for Energy is 52 mm, in close agreement with the ball target results. Note that the distribution of points about the peak response in each case is broad and establishing exact maximum positions can only be done to approximately ± 2 mm.

6.4.1.2 Planar pulse-echo target

Measurements of the on-axis profile of the same 5 MHz unfocused transducer using the extended glass reflector were also carried out, according to the guidelines specified in AS 1355 (see Section 2.3.3). These produced a spatial variation which, if it had a peak at all, appeared to be very close to the transducer face, and then steadily reduced, with no apparent indication of a subsequent increase at the last axial maximum position. This trend can be seen in Figure 6.1. A similar variation was also seen with the 2.5 MHz and 1 MHz transducers investigated.

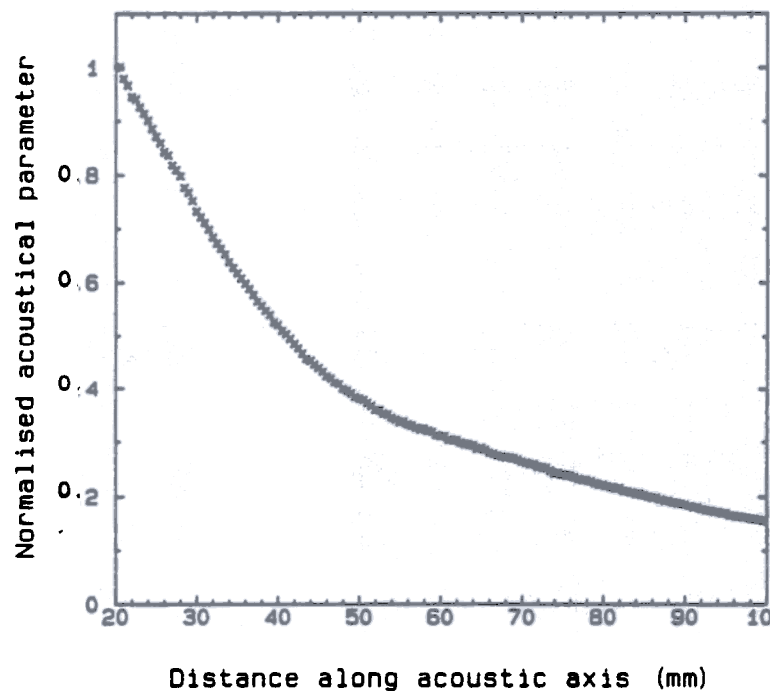


Figure 6.1: Axial variation in energy for 5 MHz unfocused transducer F11941135, measured using a planar glass pulse-echo target

There are two explanations why a distinct peak has not been observed when using the planar reflector. The first lies in the fact that the 60 mm diameter target behaves effectively as an infinite reflector when compared to the wavelength at 5 MHz. If the transducer-target separation is z , the situation may be modelled as two identical transducers facing one another at a separation of $2z$. Diffraction calculations for this configuration may be found in Figure 10.3, where the diffraction loss in dB is presented against the separation (given by

2z). The figure illustrates the steady increase in diffraction loss with separation so that with the planar (glass) target positioned at Y_{0+} (approximately at 50 mm), the loss will be -2.7 dB.

Additionally, as has already been shown in Section 4, the acoustic waveform generated by this transducer is distorted and therefore nonlinear losses will occur in the water path. Due to the high reflection coefficient of the water-glass interface, these will arise during propagation both to and from the reflecting surface. Such losses will manifest themselves as an "enhanced attenuation", with the drop in signal level over a given distance being greater than that expected for a linear regime. The effect on absolute measurements of attenuation is assessed in Section 10.

This argument is reinforced by examining the results obtained on the same transducer using a disc pulse-echo target (Figure 6.2). In this case, a clear on-axis peak is seen, as is some near-field structure. This trend of only a small local increase in signal level when making measurements on unfocused transducers was described in the Panametrics guidance document (Section 2.5), and will be the reason behind some of the Standards recommending the use of pulse-echo targets which are only a few wavelengths in diameter.

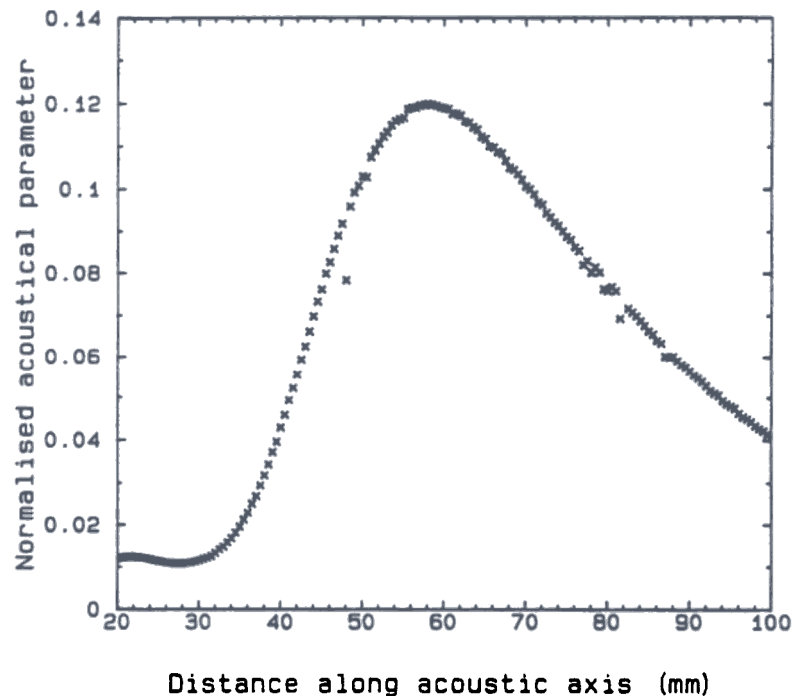


Figure 6.2: Axial variation for the 5 MHz unfocused transducer F11941135, measured using a 1 mm disc pulse-echo target, determined for the parameter $ppsi$

In considering the parameter used for determining the Y_{0+} position, the pulse-echo case shows little variation between the maximum positions indicated by the peak-positive and peak-negative voltages, and the pulse energy due to the narrow bandwidth of the pulse-echo technique.

6.4.2 Focused transducers

6.4.2.1 Hydrophones and small targets

A larger number of measurements were made on focused transducers, due to the greater importance of determining their axial response and a selection of these results is provided.

Table 6.2: Results obtained on the 5 MHz focused transducer F01951170. All pulse-echo data acquired with 1 MHz high pass filter in place

Device	<i>ppsi</i> focus /mm	-6 dB (-3 dB) focal zone (mm)
0.5 mm hydrophone	34	58.1 (34.6)
0.5 mm hydrophone [§]	27	36.3 (20.6)
1.5 mm ball	28	26.1
5 mm ball	28	28.4
1 mm rod	29	25.6

[§] 6 MHz low pass filter used.

The agreement between the focal positions determined using the pulse-echo devices is generally good, as is the focal zone or focal depth data. When the hydrophone signal is limited to an upper frequency of 6 MHz, (the -3 dB centre frequency was 3.81 MHz) agreement between the focal positions derived and those obtained from the pulse-echo cases is improved. However, the focal zone data (compared at the -3 dB and -6 dB levels for the hydrophone and pulse-echo target cases respectively) does not show such good agreement, with the filtered hydrophone data producing a focal zone which is approximately 25% less than that seen for the pulse-echo measurements, all of which agree to around 10%. Investigation of the pulse waveforms obtained at the focal positions, and examination of their frequency composition, for each profiling device, shows that there is a subsidiary high frequency component in the pulse-echo responses of the 1.5 mm and 5 mm targets. This is centred at around 7.5 MHz (the second harmonic) in both cases, with an amplitude of approximately 50% of the fundamental component. Figure 6.3 shows the 5 mm ball case.

This contribution is also present (at a reduced level of 30%) in the response of the 1 mm rod. This lower level is due to the increased spatial averaging effects of the larger reflecting area (compared to the ball targets). The -3 dB beamwidth of harmonic components decreases as the root of the harmonic number, so for a beamwidth of 1.6 mm at the fundamental frequency (3.81 MHz), the 7.6 MHz component will have a beamwidth of approximately 1.1 mm.

The use of the 6 MHz low pass filter in the hydrophone measurements excludes the second harmonic component. The effect of higher harmonic components present in the acoustic pulse would be to increase the apparent position of the focus (this is shown by the unlimited bandwidth hydrophone data, and there is a slight variation in the focal positions noted in Table 6.2, which is in sympathy with the height of the extra frequency component), and also to the increase in size of the focal zone. Hence, it is likely that the discrepancy between the filtered hydrophone data and the pulse-echo case is due to the sharp 6 MHz

cut-off of the hydrophone signal, and if the pulse-echo data had been similarly limited to 6 MHz, agreement between the focal zones may have been better.

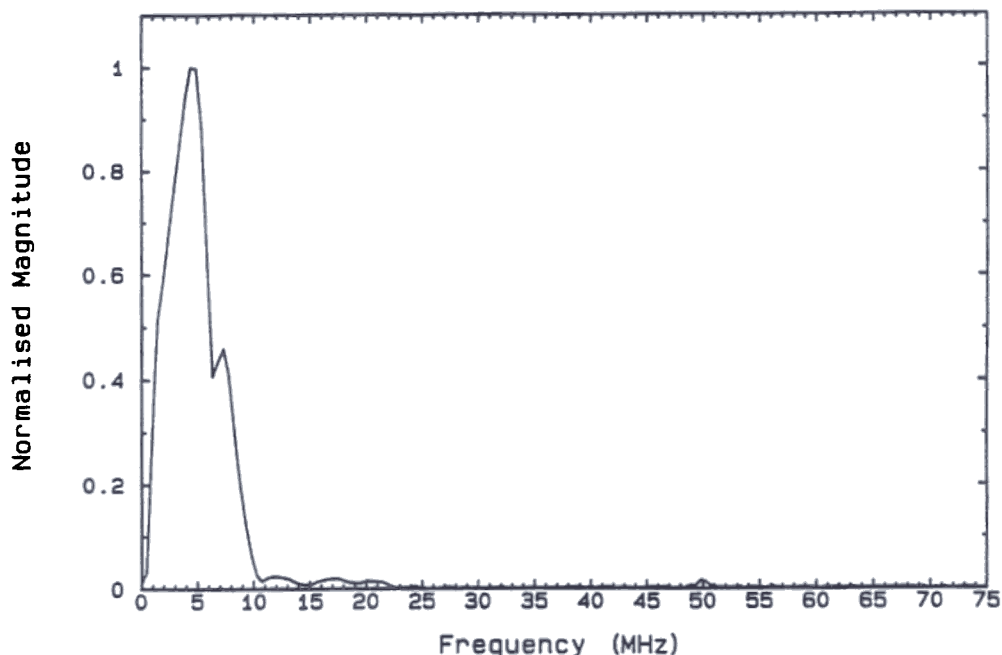


Figure 6.3: FFT of acoustic waveform measured from 5 mm ball at focus of 5 MHz focused transducer, F01951170

Table 6.3: Results obtained on 10 MHz focused transducer F10941099. All pulse-echo data acquired with 1 MHz high pass filter in place.

Device	Focus (mm)	-6 dB (-3 dB) focal zone (mm)
0.5 mm hydrophone	53	51.6 (32.2)
0.5 mm hydrophone [§]	51	55.2 (36.4)
1.5 mm ball	52.5	33.6
5 mm ball	52	34.6
1 mm rod	50.5	37.2

[§] Measurement bandwidth limited to 20 MHz.

Again, agreement between the focal positions and focal zones determined using both hydrophones and pulse-echo targets is good, even when the hydrophone is not bandwidth-limited. Note that there is a difference of only 2 mm between the focal positions determined using filtered and unfiltered hydrophone data. This is because using the high bandwidth drive setting produces a lower acoustic pressure amplitude at the transducer face, and hence reduces the extent of nonlinear propagation in the medium. This in turn limits the number of higher frequency components, and the consequent effects on the measured spatial parameters are minimal. Agreement is therefore better for this transducer than for

the 5 MHz device described above. Figure 6.4 shows the axial profiles for three of the measurement devices, for the *ppsi* case.

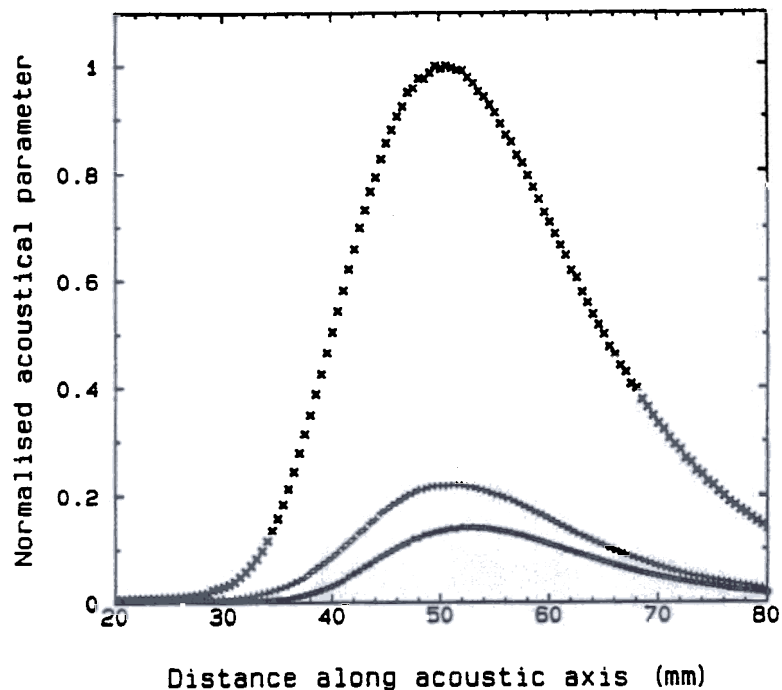


Figure 6.4: Axial response of the 10 MHz focused transducer (F10941099) to three pulse-echo targets, for the parameter *ppsi* in each case (× - 1 mm rod, + - 5 mm ball, • - 1.5 mm ball)

6.4.2.2 Planar pulse-echo target

The trend seen when using a large flat reflector to investigate the on-axis spatial distribution of unfocused transducers does not manifest itself when making measurements on focused devices. The explanation for this resides in the focusing itself, with the “gain” produced being of sufficient order to dominate. The expected axial peak, indicating the focal point, is clearly seen for the 5 MHz case (Figure 6.5). The focal position of 46 mm compares to 41 mm measured using a 0.2 mm unfiltered hydrophone. Note that these two measurements were completed prior to the 5 MHz focused transducer failing, whereas Table 6.2 contains measurement data acquired after the required repair. (Note that the focal position measured with an unfiltered hydrophone changed from 41 mm to 34 mm).

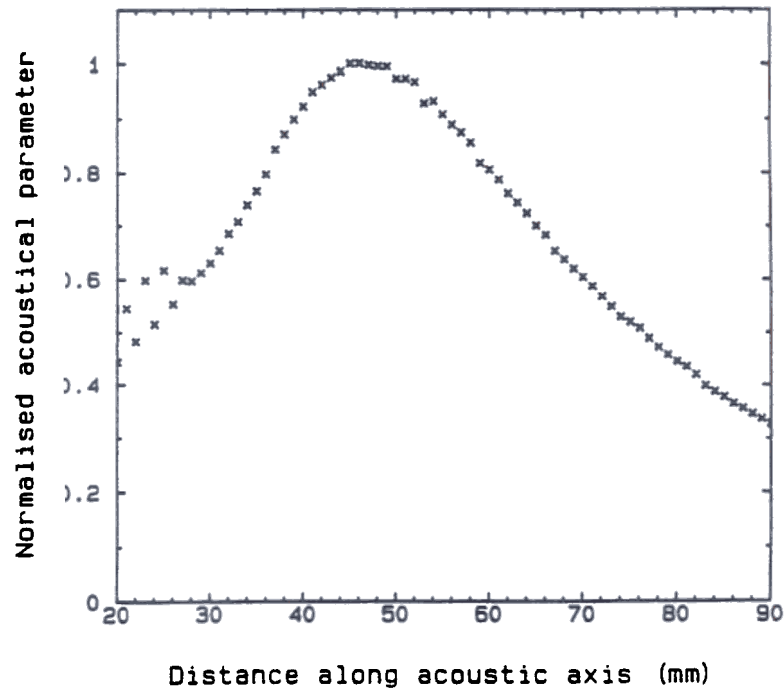


Figure 6.5: Axial response of the 5 MHz focused transducer (F01951170) to a planar pulse-echo target, for the parameter $ppsi$.

6.5 SPECIAL CASE - SHORT ACOUSTIC PULSES

Previous work completed at DERA⁷ had reported problems with the determination of the pulse-echo axial response of unfocused transducers using ball pulse-echo targets. Specifically, these manifested themselves as a series of extremely sharp peaks in the axial response (of unexpectedly high amplitudes) with the ball target located at certain positions within the transducer near-field. However, such effects were not seen in the measurements made with the Meccasonics transducers described above, possibly due to the starting position of the scan being restricted to $0.2 \cdot Y_{0+}$, and also because the less-well damped transducers produced acoustic waveforms which contained several cycles, which may have smeared out such a sharp response. To investigate this phenomenon further, a series of studies were performed on a different transducer both to elucidate the mechanism and to assess the implications for the Part 2: Calibration Procedure.

6.5.1 Demonstration of the enhanced pulse-echo response close to the transducer

Investigations were carried out using a Panametrics 10 MHz transducer of diameter 12.7 mm, driven using the low frequency setting of the Meccasonics unit to produce an almost single-cycle pulse of ultrasound, at a peak frequency of 4 MHz. The benefit of using the single-cycle pulse is that it provides the capability to identify various component echoes from the ball pulse-echo target.

Figure 6.6 gives the acoustic waveform measured using a PVDF membrane hydrophone placed on the acoustic axis at a distance of 10 mm from the transducer face. The figure clearly shows the first-arrival of the plane-wave contribution followed by the edge-wave emanating from the periphery of the transducer. Figure 6.7 gives the acoustic waveform determined at the position of the last-axial maximum (Y_{0+}) which for this transducer was determined to be at a distance of 105 mm.

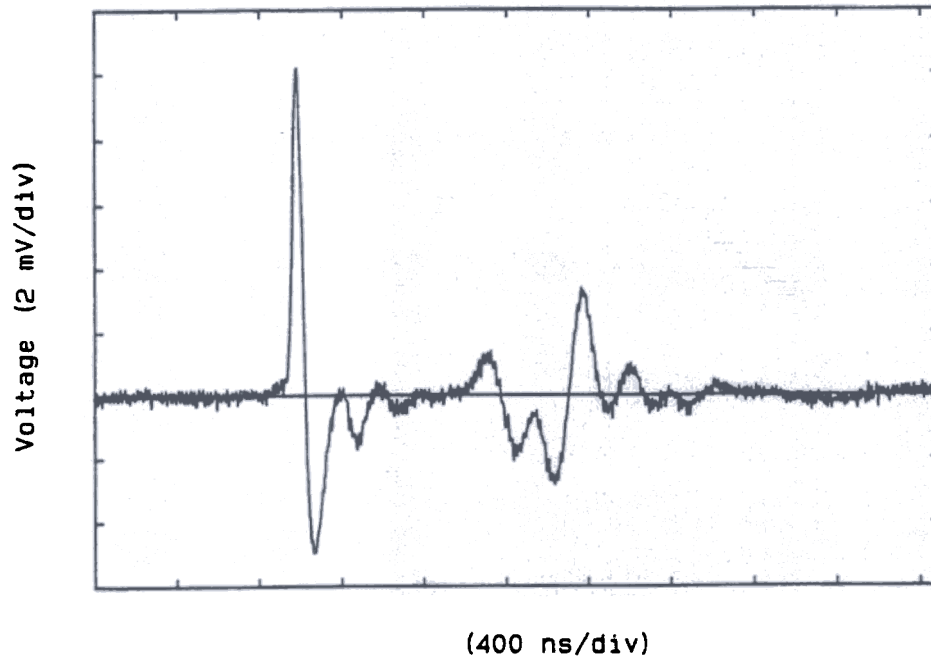


Figure 6.6: Acoustic waveform generated by the nominal 10 MHz Panametrics transducer determined using a membrane hydrophone at a distance of 10 mm from the face of transducer.

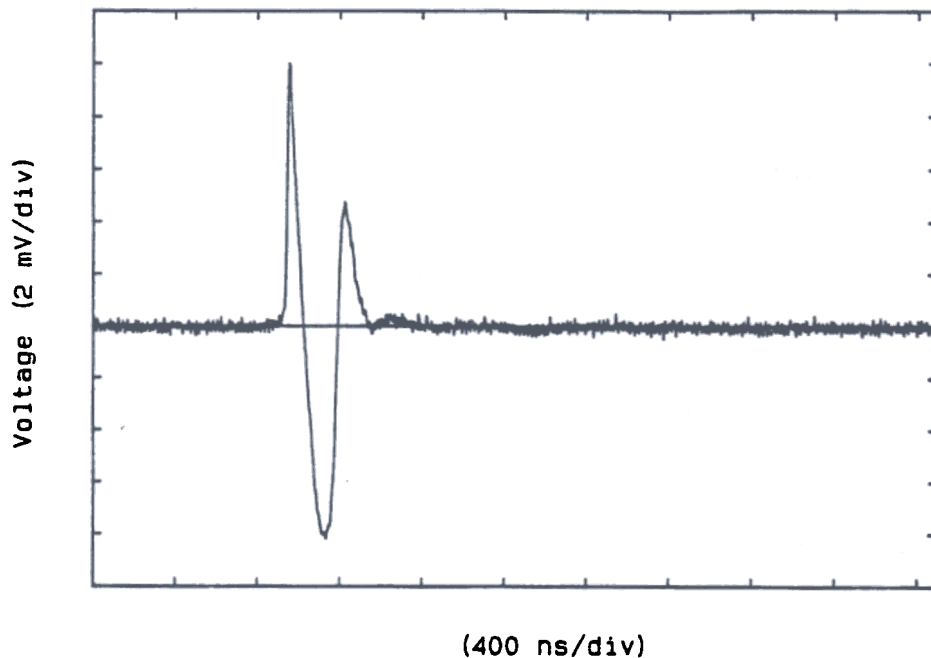


Figure 6.7 Acoustic waveform generated by the nominal 10 MHz Panametrics transducer determined using a membrane hydrophone at a distance of 105 mm, corresponding to the position of the last-axial maximum.

The pulse-echo axial response of this transducer was determined initially using ball pulse-echo targets, whose diameters met the criterion set down in Appendix D, namely that the

diameter should be less than $0.1 \cdot Y_{0+}$. Figure 6.8 and Figure 6.9 show the pulse-echo axial response determined using the 5 mm diameter ball target after careful alignment of the target on the acoustic axis of the transducer for the measured peak-positive and peak-negative waveform voltages respectively.

Both indicate strong structure in the response at separations less than 20 mm, the peak in the response being typically a factor of three higher than the signal level at Y_{0+} . It should be noted, however, that the Y_{0+} value for both parameters actually occurs in the range 105 ± 5 mm and is therefore in good agreement with the hydrophone-derived values.

Figures 6.10 and 6.11 show the peak-positive and peak-negative voltage response for the region close to the transducer ($z < 22$ mm) in more detail for two ball pulse-echo targets, of diameters 5 mm and 1.5 mm. Qualitatively, the structure shown by the pulse-echo axial response in the two ball target cases is very similar, although there appears to be a slight shift to greater distances for the positions of the peak produced by use of the smaller ball target. These peaks are clearly caused by the interaction of the ball target with the plane and edge-wave components of the transducer field. To identify more information regarding the mechanism of the interaction, a series of pulse-echo waveforms were acquired at various axial positions of the ball target, and these are described in the next sub-Section.

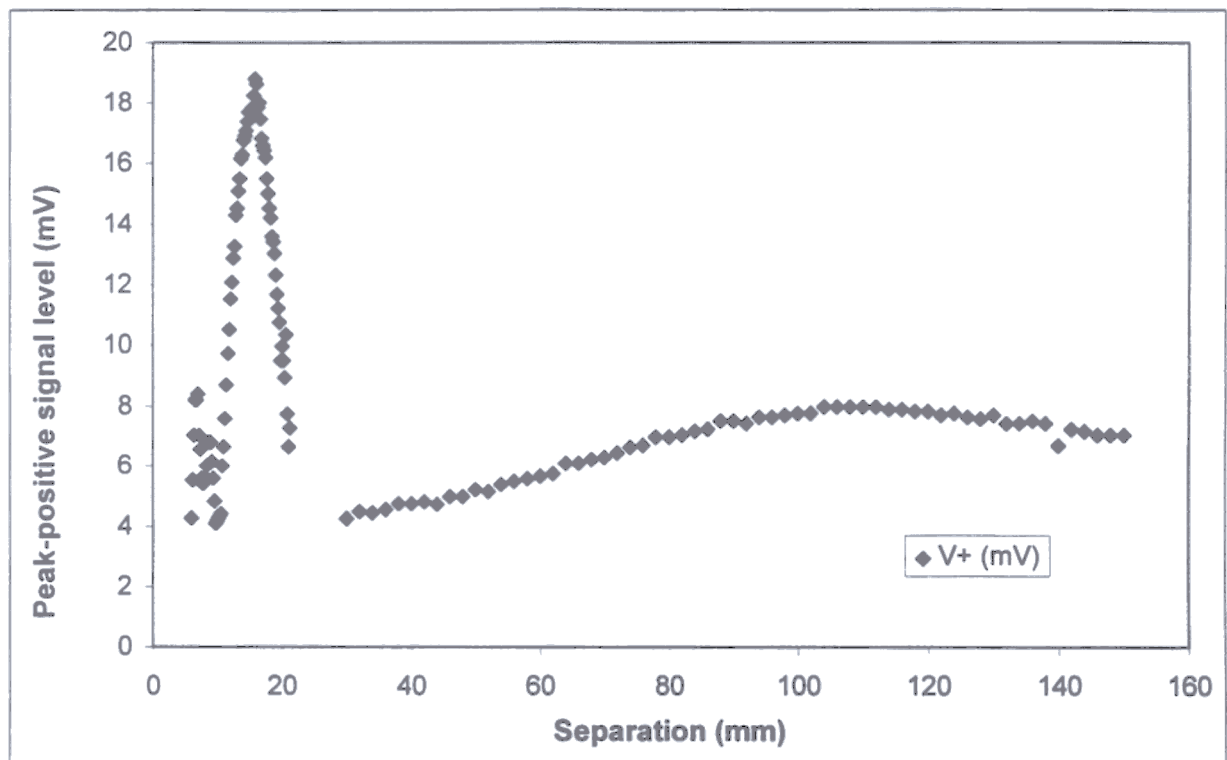


Figure 6.8: Pulse-echo axial response of the 10 MHz transducer determined using a 5 mm diameter ball target for the measured peak-positive voltage of the echo waveform

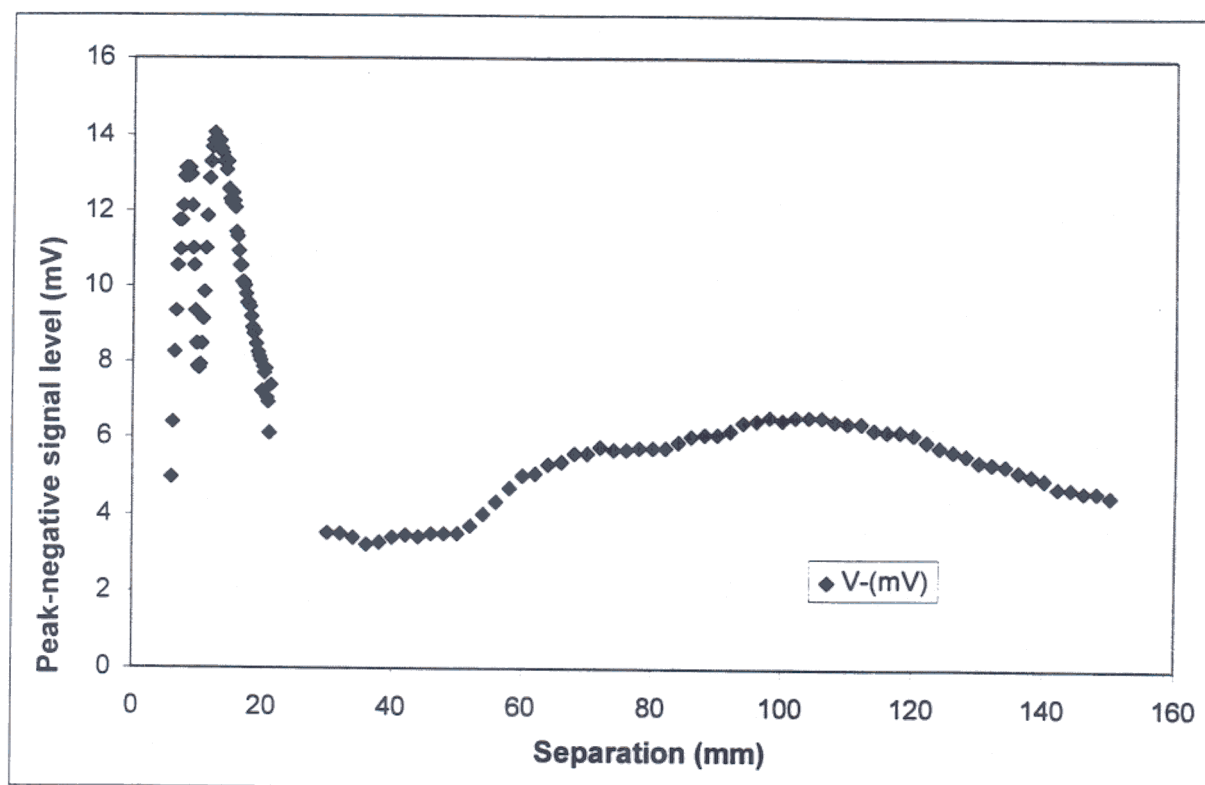


Figure 6.9: Pulse-echo axial response of the 10 MHz transducer determined using a 5 mm diameter ball target for the measured peak-negative voltage of the echo waveform

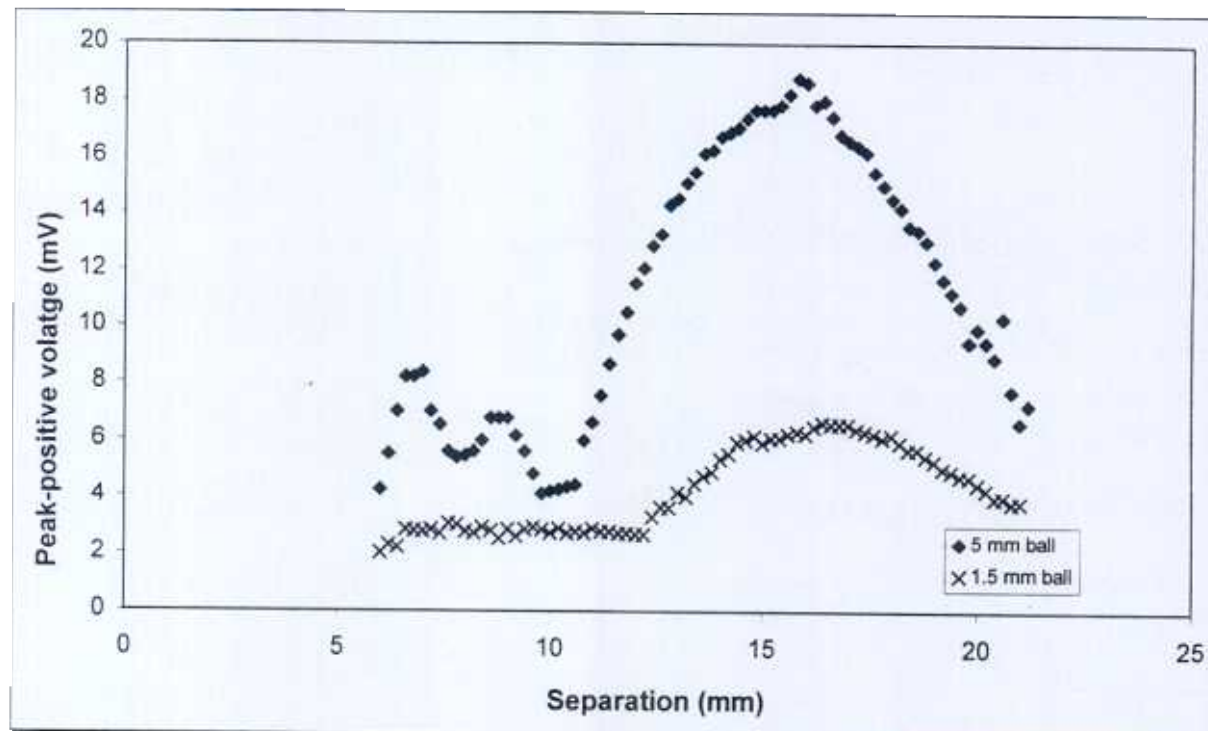


Figure 6.10: Pulse-echo axial response of the 10 MHz transducer determined using ball targets of diameter 1.5 mm and 5 mm for the measured peak-positive voltage of the echo waveform. The response has been determined over the region close to the transducer, within its plane-wave region

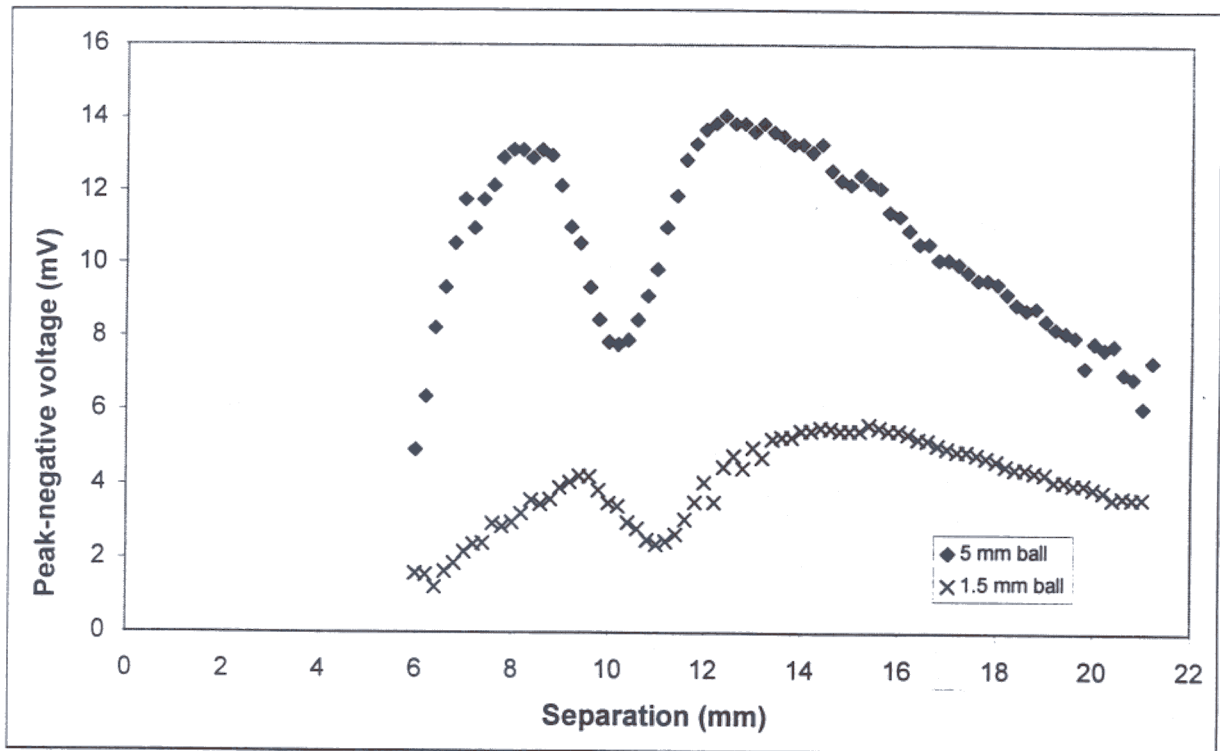


Figure 6.11: Analogous to Figure 6.8, but displaying the peak-negative voltage

Pulse-echo waveforms determined using a small ball target for $z < \frac{1}{2} Y_{0+}$

Figure 6.12 shows the pulse-echo waveform derived with the ball target placed at a distance of 8 mm from the transducer, corresponding to the position of maximum peak-negative voltage shown in Figure 6.11. The plane-wave first arrival may clearly be seen, followed by a strong negative pulse which is extremely sharply defined: even the slightest cross-axial movements of the ball target off-axis destroyed the peak-negative voltage. The sensitivity of this feature of the waveform to positioning may be used to align the ball target accurately on the transducer acoustic axis for small separations.

Figure 6.13 shows the pulse-echo waveform produced with the ball target placed at 15 mm, the position which corresponds to the positive-voltage maximum shown in Figure 6.10. The plane-wave is still evident, as is the second much larger pulse and further lower amplitude echoes.

Origin of enhanced response

Modelling of the effect lies beyond the scope of the current project and is highlighted in Section 12 as an area requiring further work. However, it is valuable to consider, in quite qualitative terms, the origin of the effect. In considering the interaction between the ball target and the transducer, it is necessary to consider the following contributions:

the plane-wave component from the transducer is the first to arrive, as demonstrated in Figure 6.12 and 6.13, and arises from the point of the ball target placed on the transducer acoustic axis. The resultant wavefront after reflection by the ball may not actually be spherical and additionally, there will be substantial spatial-averaging of the pressure over the transducer surface. This will tend to decrease as the ball target is moved away

from the transducer, and as the wavefronts over the transducer become more planar. On this basis (ignoring small signal attenuation) the plane-wave component would be expected to increase in amplitude with increasing separation. Against this, as the transducer is moved away, the effective response area of the ball target becomes smaller which may counteract or mediate this effect. There will also be a second component arising when the wavefront sweeps across the periphery of the transducer;

for the edge-wave, there will always be a part of the ball target where the edge-wave (first arrival) is incident normally. At times greater than this first edge-wave arrival back to the transducer face, the reflected edge-wave will sweep across the transducer surface. The enhanced pulse-echo axial response may arise due to the interaction of the second plane-wave component described above and the normally-reflected edge-wave component (first arrival), which is an inverted version of the plane-wave. It is also worth highlighting here the work of Weight and Hayman⁸ who reported an enhanced edge-wave effect (which they referred to as edge-wave focusing) close to the transducer. This will serve to accentuate the interference phenomena observed and the complexity of the pulse-echo response in the region.

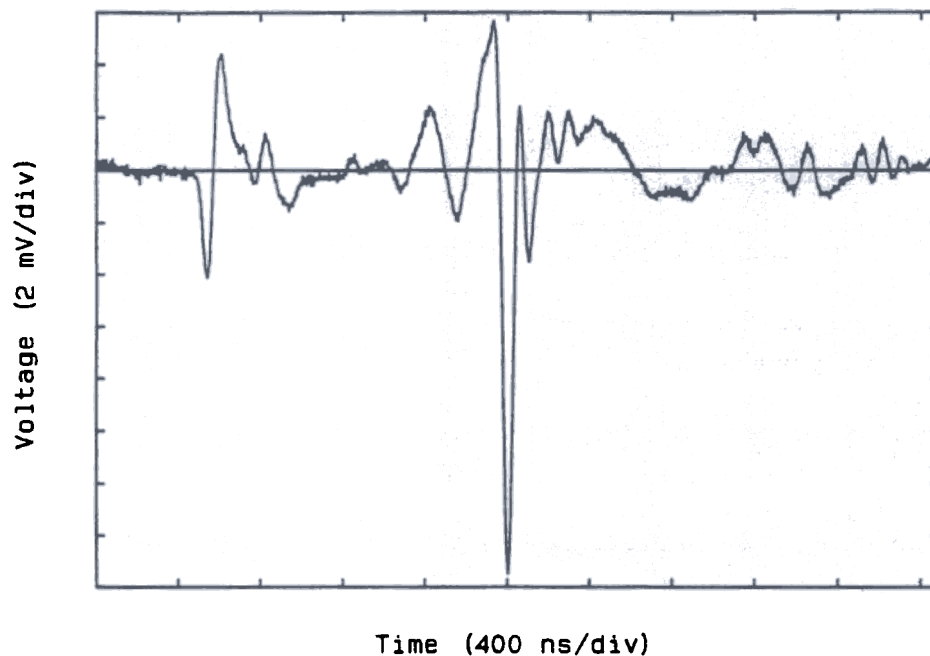


Figure 6.12: Pulse-echo waveform derived from the 5 mm diameter ball target positioned at a distance of 8 mm from the 10 MHz transducer

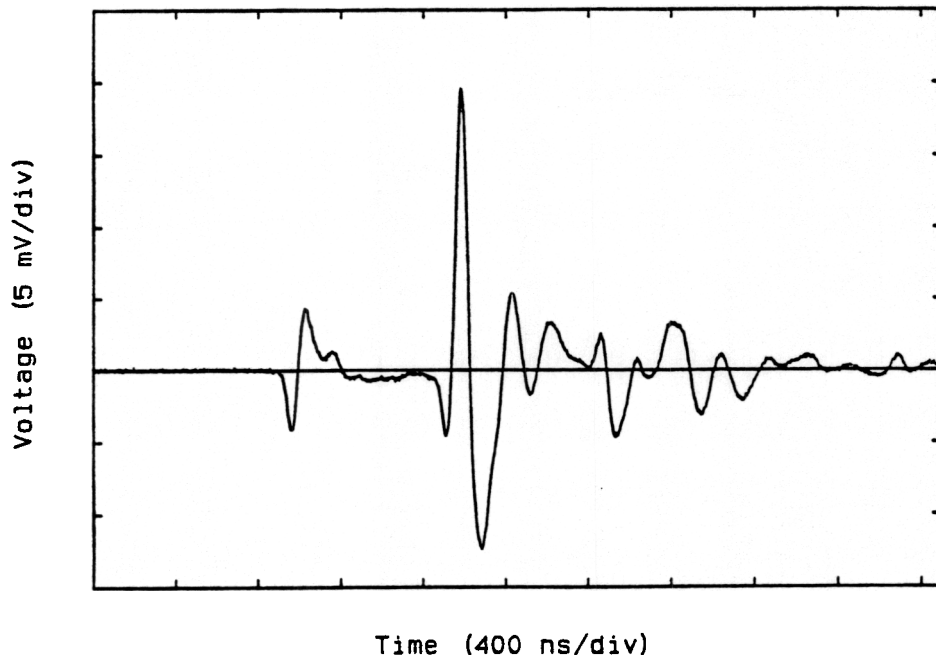


Figure 6.13: Pulse-echo waveform derived from the 5 mm diameter ball target positioned at a distance of 15 mm from the 10 MHz transducer

6.5.4 Implications for the Part 2: Calibration Procedure

There is little doubt that the enhanced response in the pulse-echo axial response arises due to interaction of plane and edge-wave components generated by the transducer. In order to reduce the effect it is necessary to work in a region of the acoustic field where the difference in arrival times of the plane-wave and edge-wave components at the ball target is small. This necessarily means working outside of the plane-wave region of the transducer.

Specifically, this means restricting the axial plot to distances $> \frac{1}{2} Y_{0+}$. It means that beamwidth information derived for closer separations is not reliable as the measurements will be influenced by the axial interactions demonstrated. In situations where beamwidth information close to the transducer face is required, an alternative means of measurement should be used such as hydrophones or disc pulse-echo targets.

However, taken overall, in terms of the Part 2: Calibration Procedure, the most important conclusion which can be made is that the position of the last axial maximum, Y_{0+} can be determined reliably, even in situations where this enhanced interaction occurs.

6.5.5 Pulse-echo waveforms derived from ball target measurements at $z > \frac{1}{2} Y_{0+}$

The pulse-echo waveforms determined using three different sizes of ball target are shown in Figures 6.14, 6.15 and 6.16. The diameters of the ball targets are 1.5 mm, 5 mm and 10 mm and each is positioned on the acoustic axis at a distance of 105 mm from the transducer (Y_{0+}). Note the similarity between each of the waveforms, the appearance of an extra

contribution for the 1.5 mm diameter ball target is due to a reflection from the support mount, and also the fact that each is a reasonable approximation to the idealised point target response described in detail in Appendix E (Section E2). Using the expression for Δl_m (Appendix E3), the equivalent diameters over which the ball target respond in this configuration are 0.05 mm, 0.15 mm and 0.3 mm for the 1.5 mm, 5 mm and 10 mm diameter balls respectively. Each lies within the specification for the ball target diameter for the case of (flat) plane-piston transducers given the Part 2: Calibration Procedure.

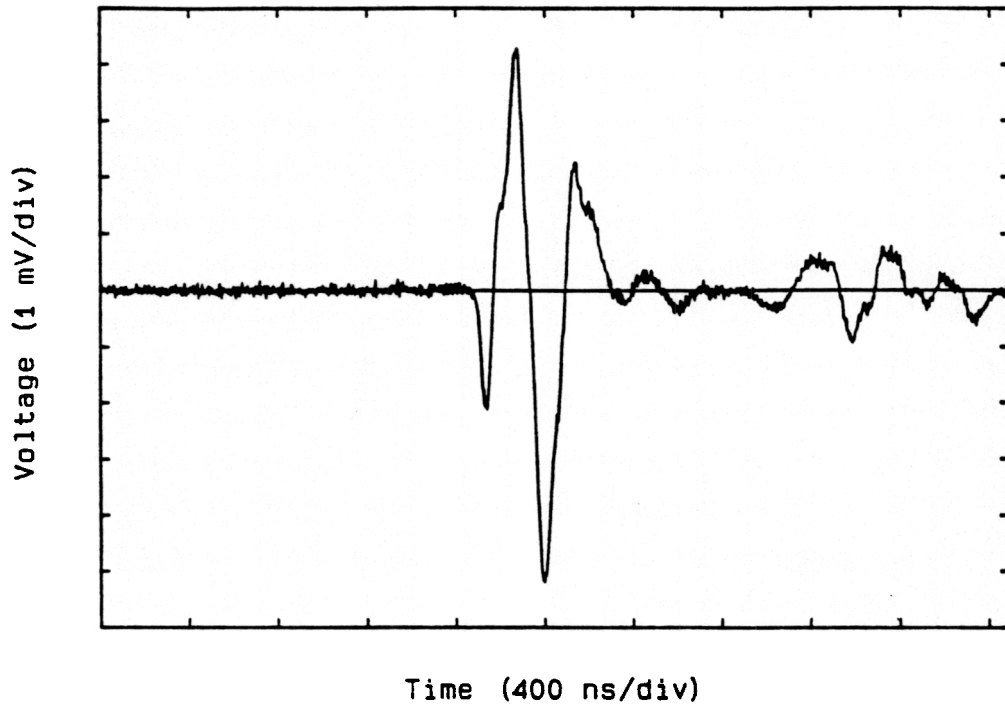


Figure 6.14: Pulse-echo waveform acquired using the 1.5 mm diameter ball target positioned at Y_{0+} (105 mm for the 10 MHz transducer)

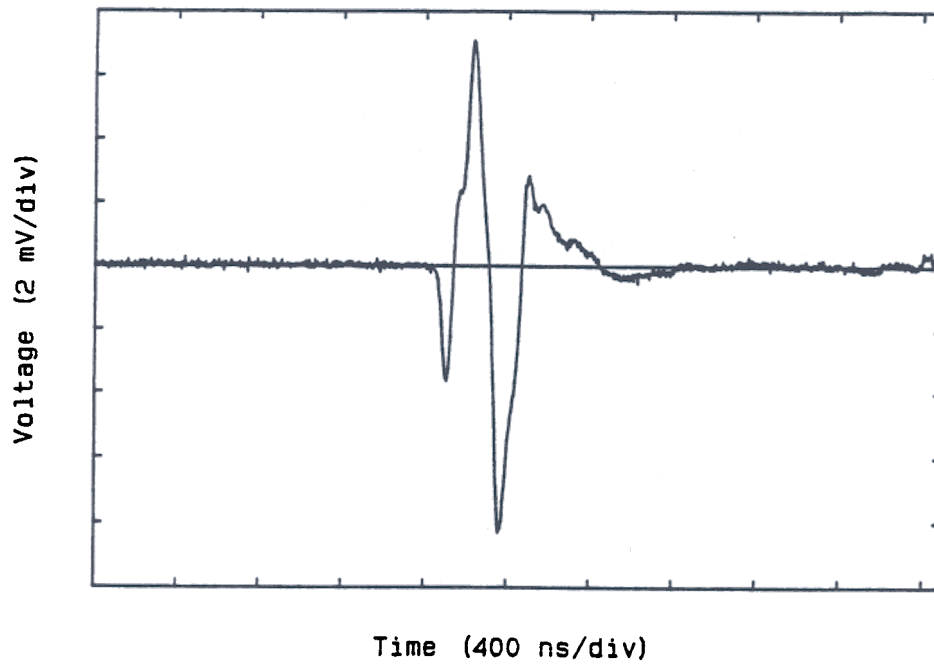


Figure 6.15: Pulse-echo waveform acquired using the 5 mm diameter ball target positioned at Y_0+ (105 mm for the 10 MHz transducer)

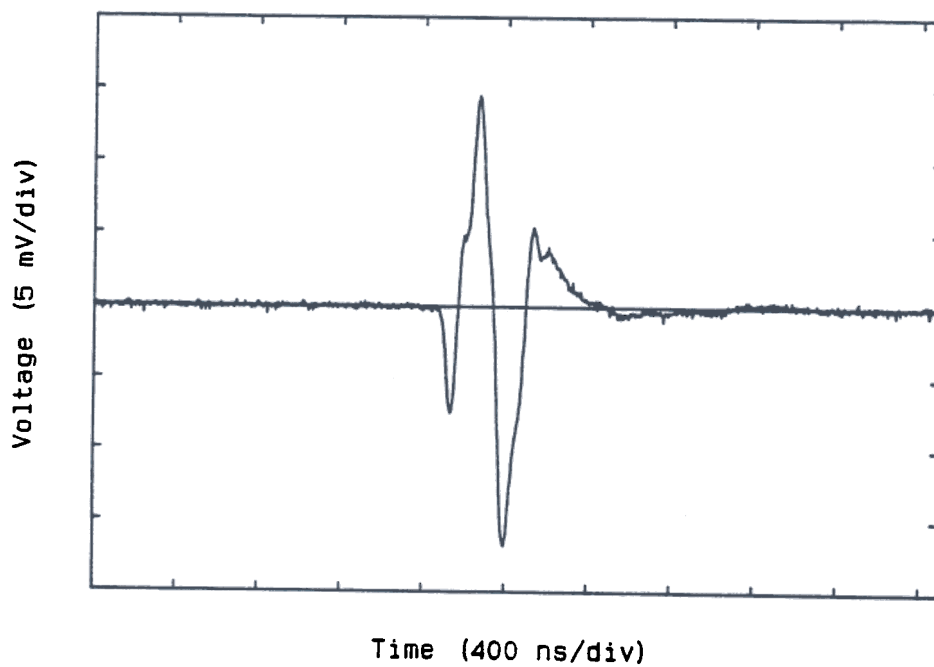


Figure 6.16: Pulse-echo waveform acquired using the 10 mm diameter ball target positioned at Y_0+ (105 mm for the 10 MHz transducer)

6.5.6 The use of disc pulse-echo targets

As indicated in Section 3, an alternative implementation of the 'point' target configuration which was studied during the project was the disc pulse-echo target, or flat-ended rod. The following describes measurements made on the 10 MHz Panametrics transducer using the 0.56 mm diameter disc target, as it was suggested that measurements made using such rods would not be subject to the structure produced by the ball target when placed relatively close to the face of the transducer. Note that both the 1 mm and 0.56 mm diameter rods fulfil the size criterion given in Appendix E.4.1.2 which identifies an upper diameter of 1.7 mm for a beamwidth measurement accuracy better than 2%.

6.5.6.1 Pulse-echo waveforms

Figures 6.17 to 6.19 show the pulse-echo waveform determined from the 0.56 mm rod at a range of distances from the transducer, the traces clearly illustrating the plane-wave component and the inverted edge-wave arriving approximately $0.4 \mu\text{s}$ later. For greater transducer separations other contributions emerge. At a distance of 79 mm, the time difference between the plane and edge-wave contributions has reduced and a third component is easily discernible. At the position of Y_{0+} , four distinct components may be identified produced by the plane and edge-wave components of the transducer diffracting from the finite dimensions of the flat-ended rod. Note that the observed pulse-echo waveform in Figure 6.19 shows distinct similarities to the ideal point reflector waveform described in Appendix E, and certainly in the limit of large z , the plane and edge components will run into one another to approach the point target waveform. For information, the equivalent waveform obtained using the 5 mm diameter ball target has been shown previously in Figure 6.15.

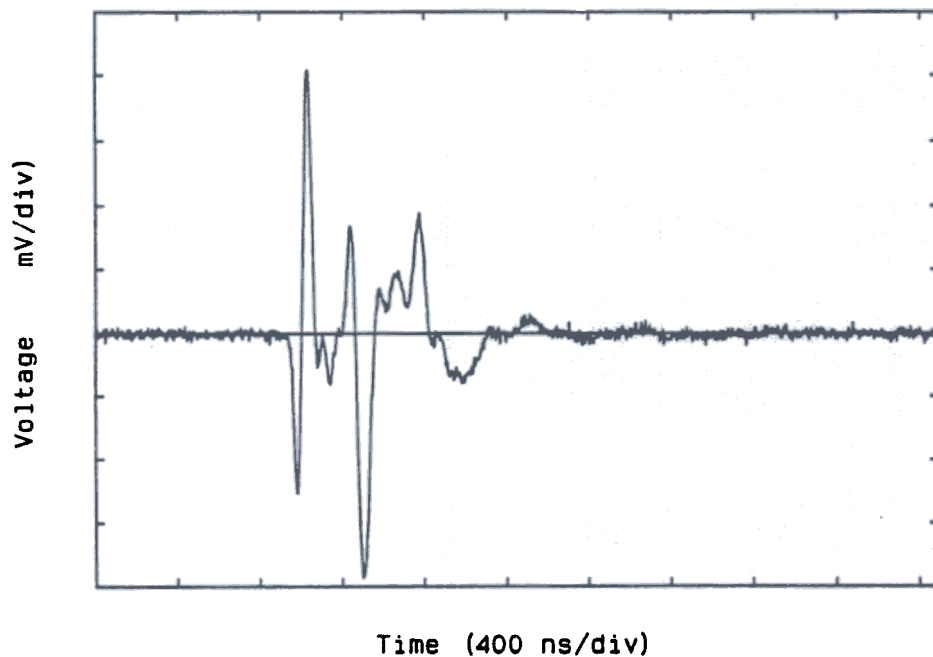


Figure 6.17: Pulse-echo waveform acquired using a 0.56 mm diameter rod target positioned at a distance of 52 mm from the 10 MHz transducer

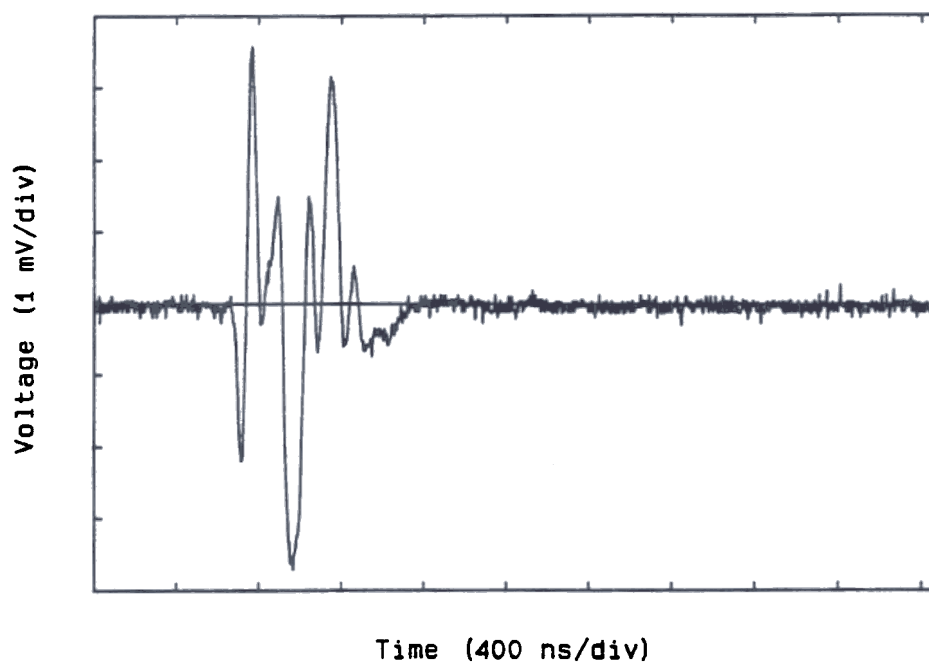


Figure 6.18: Pulse-echo waveform acquired using a 0.56 mm diameter rod target positioned at a distance of 79 mm from the 10 MHz transducer

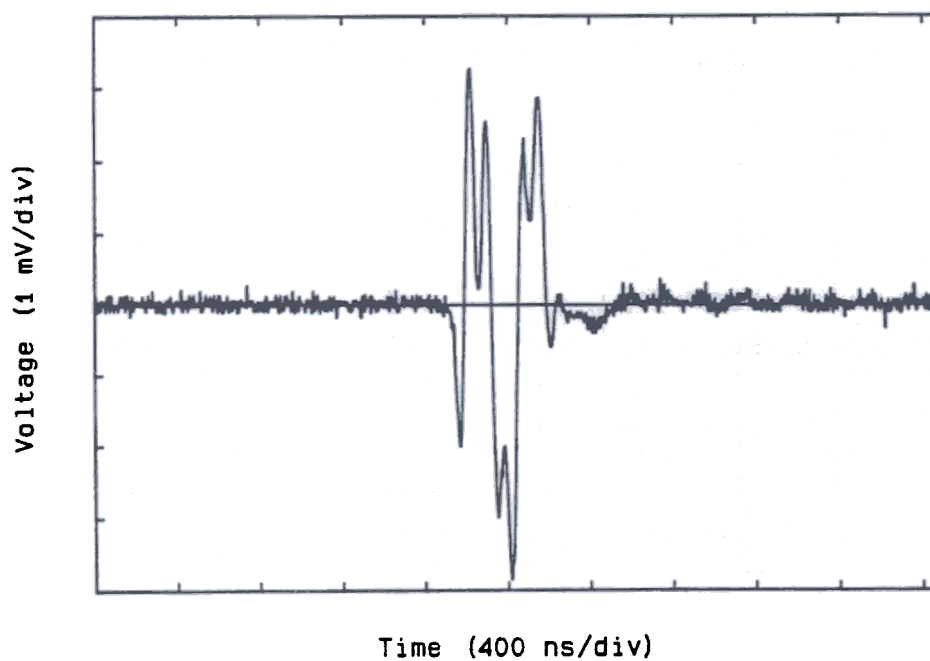


Figure 6.19: Pulse-echo waveform acquired using a 0.56 mm diameter rod target positioned at a distance of 105 mm from the 10 MHz transducer

6.5.6.2 Pulse-echo axial response

A comment was made earlier that flat-ended rods might be less susceptible than ball target scatterers to the strong structure observed with the target close to the transducer face. This was investigated using the 10 MHz Panametrics transducer through comparison of the pulse-echo axial response derived using a disc target with measurements made using the reference hydrophone system. These results are shown in the series of Figures from 6.20 and 6.21 for the hydrophone, and 6.22 and 6.23 for the pulse-echo case, for the measured parameters of peak-positive and peak-negative voltage, as well as the pulse-pressure-squared integral (*ppsi*) respectively. Note the similarity between the pulse-echo axial response derived using the *ppsi* for the hydrophone (6.21) and the disc target (6.23), both indicating a Y_0+ value in the range 105 mm to 110 mm, in close agreement with the ball target data. Flat-ended rod targets do not, therefore, appear to be prone to the strong structure described in Section 6.5.1.

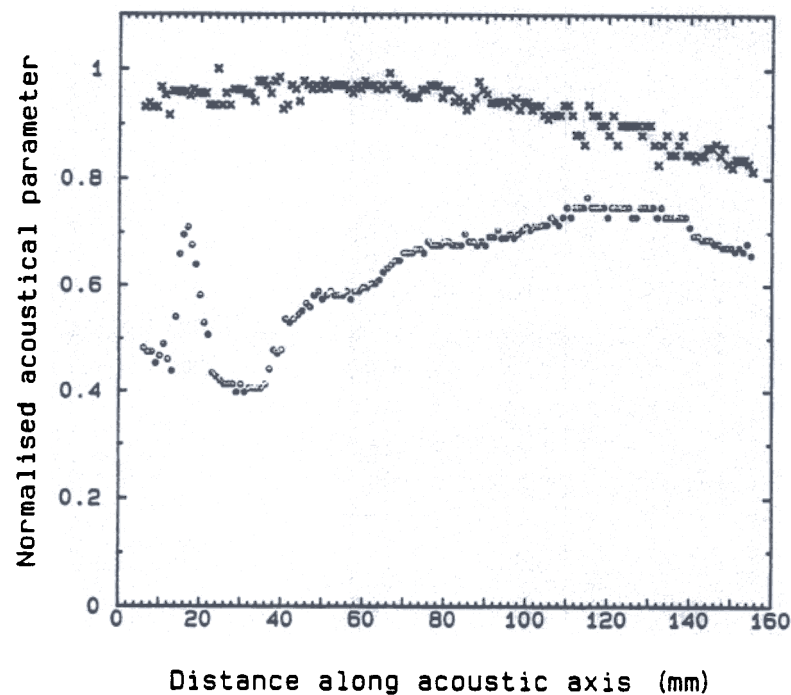


Figure 6.20: Axial response of the 10 MHz transducer determined using a membrane hydrophone for the parameters peak-positive voltage (x) and peak-negative voltage (•)

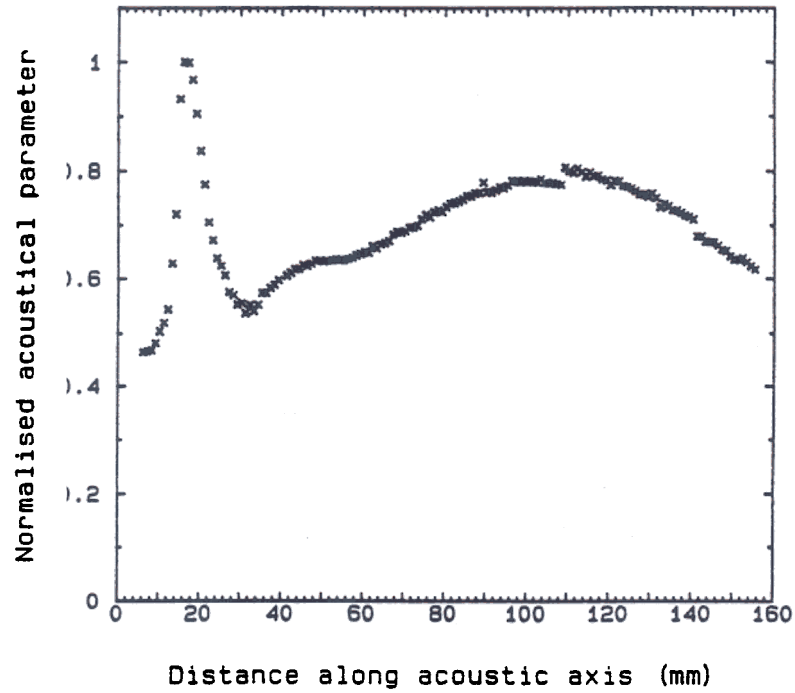


Figure 6.21: Axial response of the 10 MHz transducer determined using a membrane hydrophone, for the pulse-pressure squared integral.

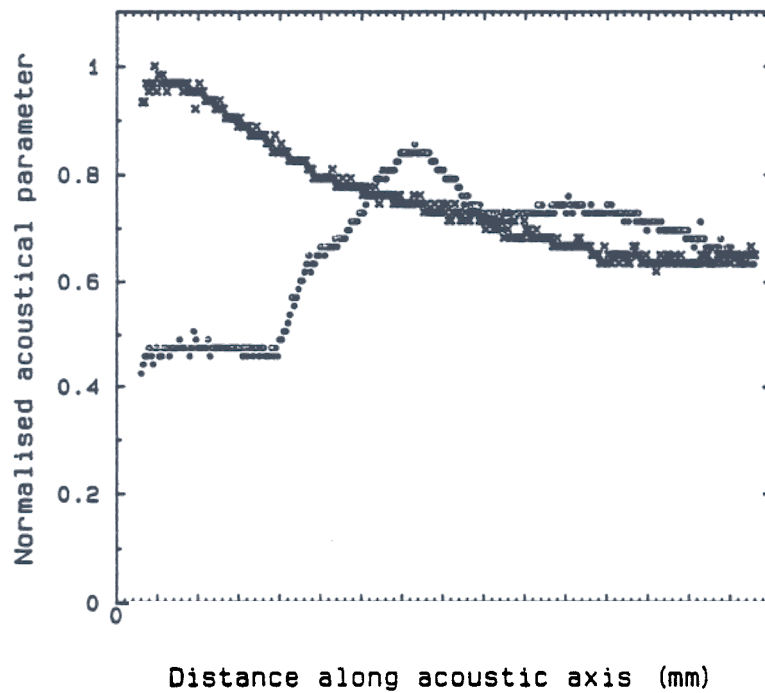


Figure 6.22: Pulse-echo axial response of the 10 MHz transducer to a 1 mm diameter disc pulse-echo target, for the parameters peak-positive voltage (x) and peak-negative voltage (•)

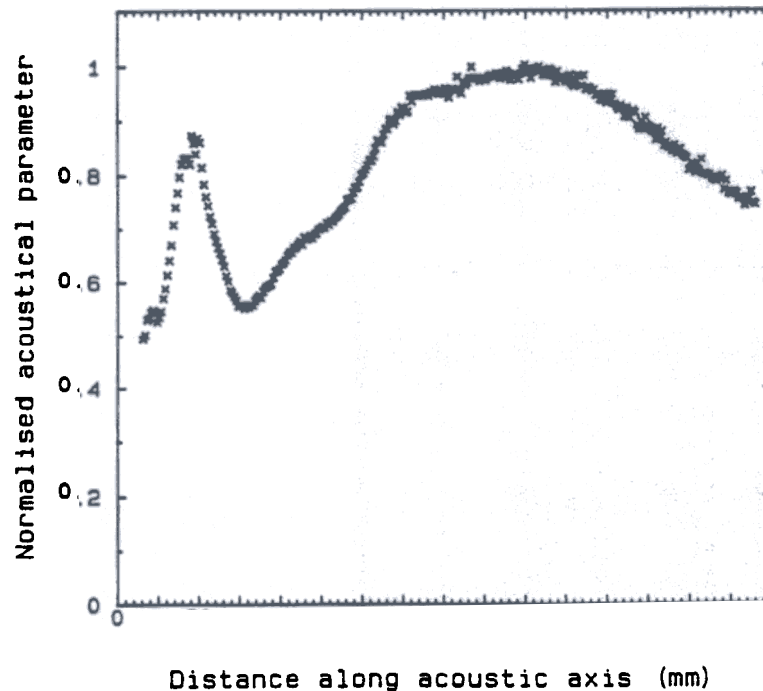


Figure 6.23: Pulse-echo axial response of the 10 MHz transducer to a 1 mm diameter disc pulse-echo target, for the pulse energy

6.6 CONCLUSIONS

The measurements and studies reported in this Section have been used to derive the requirements and protocol of the draft Part 2: Calibration Procedure. Specifically, the findings and recommendations are thus:

- both hydrophones and point-like pulse-echo targets (ball and disc types) may be used to provide information on the axial profile of focused and unfocused transducers;
- a planar pulse-echo target may not be used to determine the axial profile of unfocused transducers, although its performance is satisfactory with focused transducers;
- the relationship described in ASTM E 1065-92, stating the equivalence of the -3 dB focal zone determined using a hydrophone and the -6 dB focal zone measured using a pulse-echo technique" has been tested. Agreement is obtained only in the cases where the hydrophone bandwidth is nominally equivalent to the pulse-echo bandwidth;
- care must be taken in interpreting the data obtained from ball target measurements of unfocused transducers performed in the near-field region, as structure may be seen due to local resonances in the response which can be misleading. The position of the Y_{0+} or focal point shall be taken as that of the last axial maximum.

7 CROSS-AXIAL MEASUREMENTS

7.1 BACKGROUND

Determination of the cross-axial beamwidth of an ultrasonic beam is probably the single most important parameter to be considered in the characterisation of a transducer in any application. The beam diameter determines the spatial resolution of the system, and hence provides information on the smallest size defect that can be reliably detected by the C-scan scanning system. Standards reported in Section 2 devote much attention to the assessment of cross-axial beam parameters, and again, provide much of the basis for the pulse-echo techniques.

7.2 EXPERIMENTAL PROCEDURES

In general, system alignment is not as crucial for beamwidth determination as it is for axial profiling; however, it was still considered useful to carry out similar procedures to those described in Section 6.2 prior to measurements being performed.

Hydrophone measurements

Among the Standards, the ASTM document is alone in permitting the use of piezoelectric hydrophones in cross-axial beam profiling, the data provided being used to determine beamwidths at the -3 dB level. Using the NPL Beam-Plotting Facility a variety of hydrophone-amplifier combinations were used to investigate the distribution of acoustic pressure in the ultrasonic field. Additionally, some measurements were performed using filters, to restrict the bandwidth of the hydrophone, a technique which was used to allow comparison data with bandwidth-limited pulse-echo measurements.

Pulse-echo measurements

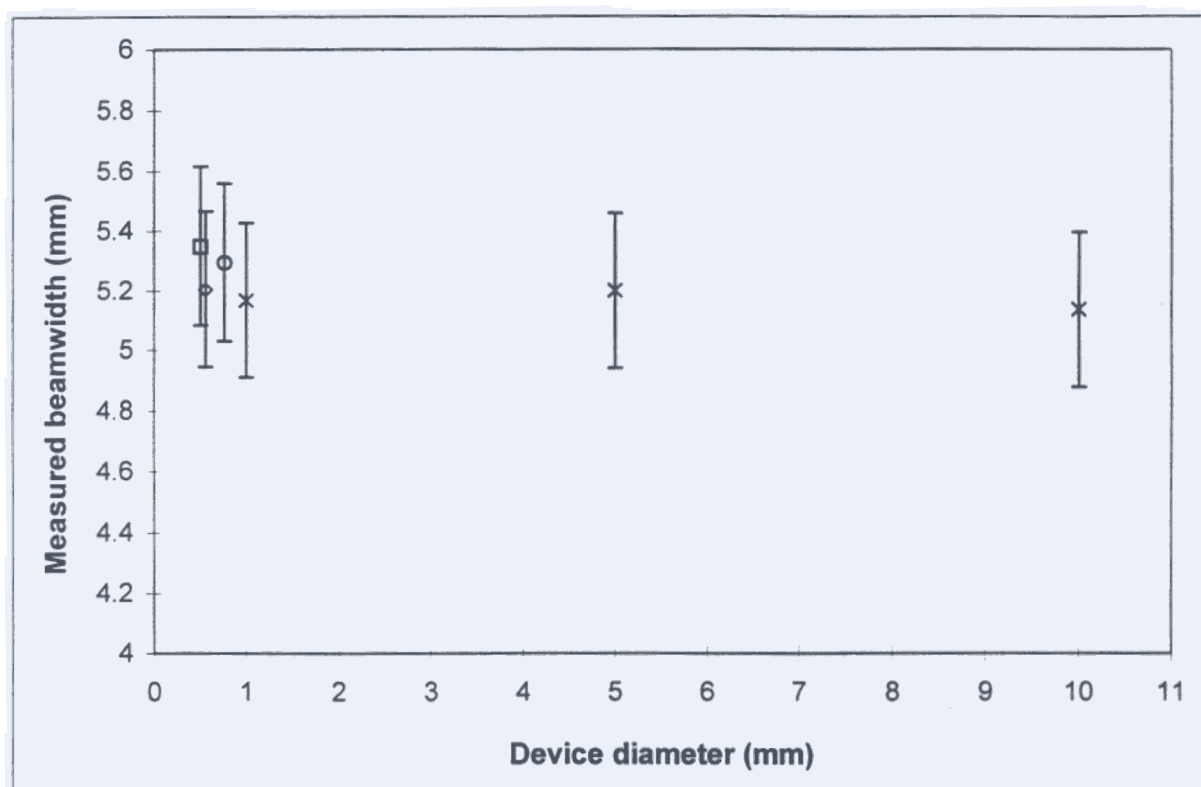
The relevant Standards recommend the use of ball targets for the determination of beamwidths at the -6 dB level, and also to investigate beam symmetry. In some cases, the Standards state the size of the targets to be used, dependent on the nominal centre frequency of the transducer under test. A range of target configurations and sizes were used and the construction of these has been described in Section 3.6.2.

7.3 RESULTS

Only a selection of the data obtained is presented. In all cases, the beamwidth values shown are calculated from an average of dimensions found in two perpendicular directions, and in most instances, from a number of repeat measurements.

Unfocused transducers

Figures 7.1 to 7.2 illustrate the results obtained on two of the unfocused transducers measured. On each graph, the measured beamwidths are quoted at either the -6 dB (for pulse-echo) or -3 dB level (hydrophone data).



□ 0.5 mm hydrophone; ◇ 0.56 mm disc; ○ 1 mm disc

Figure 7.1: Beamplot data for 1.0 MHz unfocused transducer, F1657, crystal diameter 15 mm (recorded at 42 mm separation distance). All values are derived from measurements made using ball pulse-echo targets unless otherwise stated. Error bars ($\pm 5\%$) are estimates, based on repeatability and asymmetry

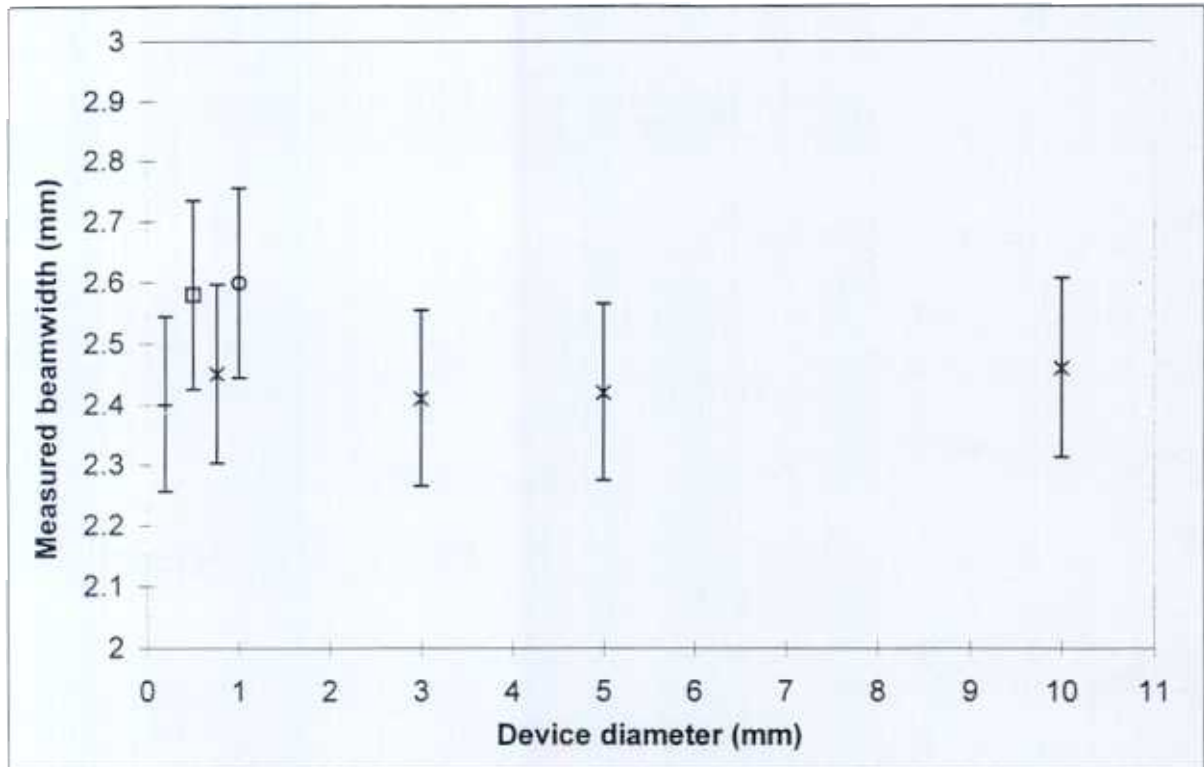
7.3.1.1 Comparison of hydrophone and pulse-echo measurements

For this transducer, the agreement over the range of pulse-echo targets used is excellent. There is no evidence of any trend in measured beamwidth with target size, even for the 10 mm diameter ball target and the disc pulse-echo targets and hydrophone data both agree well with the ball pulse-echo target values. The specifications for the hydrophone and small pulse-echo target dimensions given in Appendix E translate into the following: hydrophone (diameter < 5 mm); disc target (< 2 mm) and ball target (diameter < 8.4 mm). These specifications are readily met by the measurements and the four results are clustered to within $\pm 6\%$. It can be seen, as expected from the analysis given in Appendix E, that even using a ball target of diameter 10 mm (actually just within the $0.31 \cdot Y_{0+}$ criterion given) still produces agreement with the smaller devices.

Figure 7.2 gives results for the 5 MHz unfocused transducer F11941135. Here, the predicted beamwidth in the plane at Y_{0+} is 2.57 mm. Again, if we consider the specifications for the hydrophone and small pulse-echo target dimensions given in Appendix E, these translate into the following: hydrophone (diameter < 3 mm); disc target (< 1.35 mm) and ball target (diameter < 10.6 mm). Good agreement is again demonstrated between measurements. There is also good agreement between the two different hydrophones used.

It is useful to consider the specifications placed by existing Standards as outlined in Appendix E. These recommend small ball target diameters in the range 1.5 mm to 3 mm and hydrophone

diameters in the range 0.15 mm to 0.6 mm in the case of F11941135. It can be seen that both are unnecessarily restrictive. The effect of spatial-averaging on beamwidth measurements made using small disc targets will be considered in the next sub-Section.



+ 0.2 mm hydrophone; □ 0.5 mm hydrophone; o 1 mm disc

Figure 7.2: 5 MHz unfocused transducer, F11941135, 10 mm crystal diameter. Measurements made at 53 mm separation using a 1 MHz high-pass filter in place for all pulse-echo measurements. Values are derived from measurements made using ball pulse-echo targets unless stated. Error bars ($\pm 6\%$) are estimates, based on repeatability and asymmetry

7.3.1.2 Examination of spatial-averaging effects

The calculations in Appendix E, Section E4.1.3 indicate that for the two unfocused transducers reported here, with Y_{0+} values of 42 mm and 53 mm respectively, the diameters of any ball targets used for cross-axial profiling at distances of Y_{0+} and greater should be less than approximately 8.4 mm and 10.6 mm respectively. In most cases shown, the ball targets used fall within these requirements, and the uniformity of the derived beamwidths over the range of target sizes used indicates that the limits set are appropriate, and can hence be fed into the recommendations in the draft procedure. Even where this criterion is violated, as in the case of the 10 mm ball for transducer F1657, reliable beamwidth measurements are produced.

Some further measurements were performed on the 5 MHz unfocused transducer (F11941135), using larger disc pulse-echo targets. These were carried out specifically to investigate the extent of spatial-averaging, and to provide a limited validation of the model described in Appendix E, Section E4.1.2. The results obtained are presented in Figure 7.3.

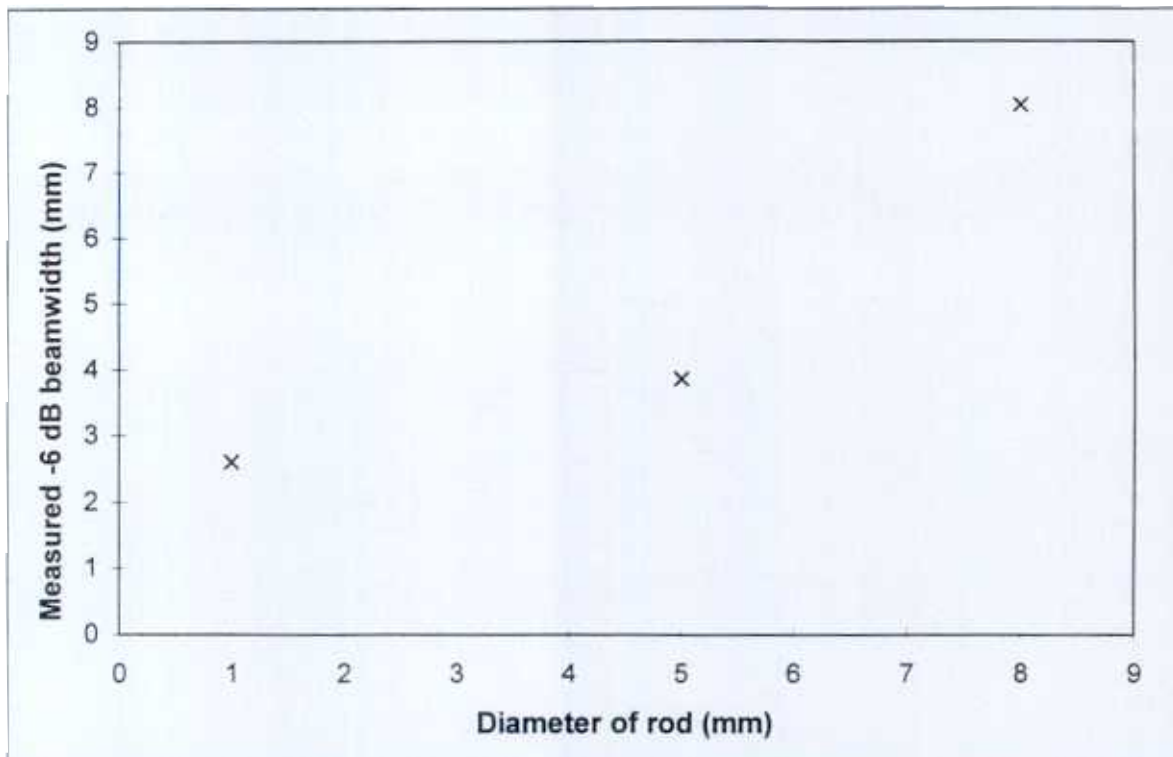


Figure 7.3: Graph of beamwidth values measured for 5 MHz unfocused transducer, F11941135, 10 mm crystal diameter, using three disc pulse-echo targets. Data acquired at 53 mm separation, with 1 MHz high pass filter used

The figure shows the anticipated trend, with the measured beamwidth increasing as a function of disc diameter. Using the analysis given in Appendix E, it is specified that for a 10 mm diameter crystal, the diameter of the disc pulse-echo target used should not exceed 1.3 mm, in order that the effect of spatial-averaging is maintained below 2%. Here, the 1 mm disc used produces a beamwidth value which agrees with the hydrophone-derived values (average of results from 0.2 mm and 0.5 mm active element diameters) to better than 5%, which is the order of uncertainty normally associated with hydrophone-derived beamwidths.

Use of the 5 mm disc produced a value of the beamwidth of 3.85 mm. The spatial-averaging calculation for this case indicates that using such a rod will produce an overestimate of around 55% in the measured beamwidth; the measured value is actually 50% higher than the “true” beamwidth. The model used for the spatial-averaging corrections would hence appear to be valid although a more extensive investigation would be desirable. In the case of the 8 mm diameter disc target, the measured beamwidth is 8.03 mm. Clearly, in this case, the disc itself is effectively being scanned, and the value derived may in fact be interpreted as the -6 dB defect width.

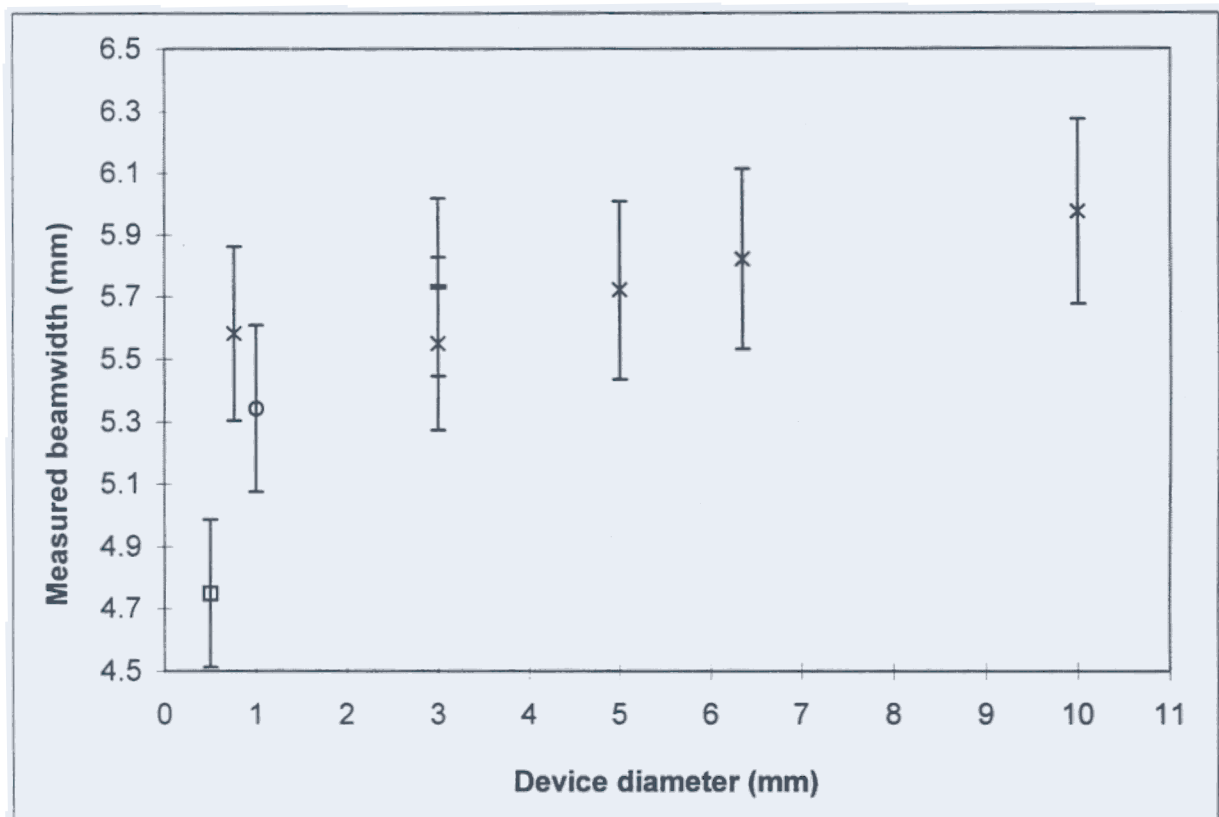
7.3.1.3 Effect of measurement bandwidth and filtering considerations

The beamwidth values derived from hydrophone measurements described above for the 1 MHz and 5 MHz unfocused transducers were all calculated from pulse energy (or *ppsi*) data. As described in Section 4 and Appendix C, the effects of nonlinear propagation can produce significant differences in beam dimensions depending on which parameter (p_+ , p_- , *ppsi*) is used. The pulse energy (*ppsi*) is comparatively unaffected by nonlinear propagation but will still be modified from the expected narrowband response. In contrast, the measured beamwidths in

p_+ and p_- were 1.3 mm and 4.0 mm respectively for the 5 MHz unfocused transducer F11941135, using a wide bandwidth (70 MHz) system. However for a 23 MHz bandwidth system, these had changed to 2.49 mm and 3.6 mm respectively. In the latter case, the *ppsi* data produced a beamwidth of 2.6 mm, compared to 2.4 mm for the 70 MHz system. This illustrates the effects that the high frequency components can have on measured parameters. In this case, limiting the bandwidth of the hydrophone system to 6 MHz produced virtually no change in the -3 dB beamwidth measured in *ppsi*.

7.3.2 Focused transducers

As described in Appendix D, the ultrasonic field produced by focused devices is likely to be more complex than that seen in unfocused cases, so predicting the ultrasonic pressure distribution, and in turn deriving requirements for pulse-echo target sizes and geometries may not be trivial. Consequently, a significant number of measurements were carried out on focused transducers to determine these requirements experimentally. Figures 7.4 to 7.6 illustrate the results obtained on a selection of the systems characterised. On each graph, the measured beamwidths are again quoted at either the -6 dB (for pulse-echo) or -3 dB level (hydrophone data).

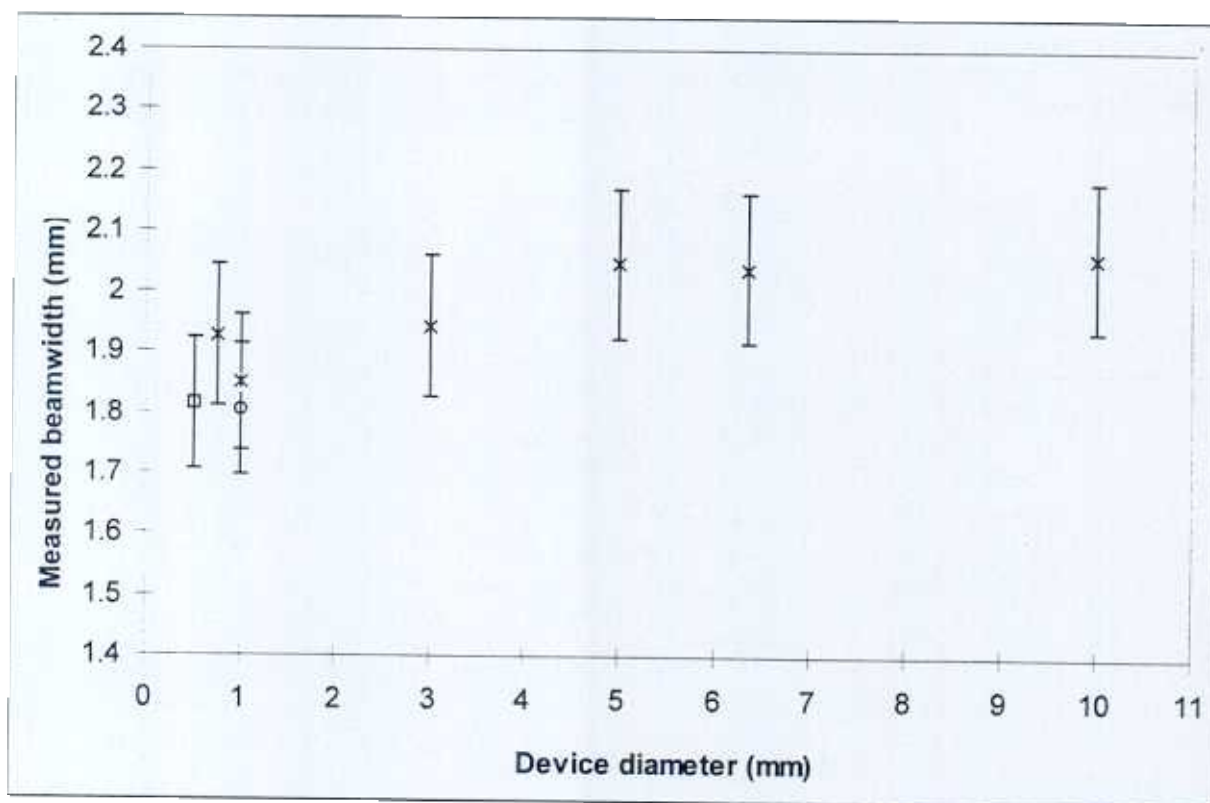


□ 0.5 mm hydrophone; ○ 1 mm disc ; × -3 mm disc

Figure 7.4: Beamplot data for 1.0 MHz focused transducer (F01951172), crystal diameter 15 mm (recorded at 54 mm separation distance), 2.5 MHz low pass low pass filter, used to reject the high frequency components. All values are derived from measurements made using ball pulse-echo targets unless stated. Error bars ($\pm 5\%$) are estimates, based on repeatability and symmetry

With the exception of the 0.76 mm target, there appears to be a clear increasing trend in measured -6 dB beamwidth as a function of ball target diameter. The agreement between the 1 mm disc target and the 0.76 mm ball target is better than 4%, although the value derived from a hydrophone of nominal active element diameter 0.5 mm produces a 12% smaller beamwidth than the two smallest pulse-echo targets. The increase in the measured beamwidth up to the 10 mm diameter ball target is 11% over the range of devices used.

Note that this transducer, as illustrated in Figure 4.7 and 4.8, generates additional frequency components at 3.3 and 5.5 MHz, resulting in a complex time-domain waveform and corresponding frequency spectrum.

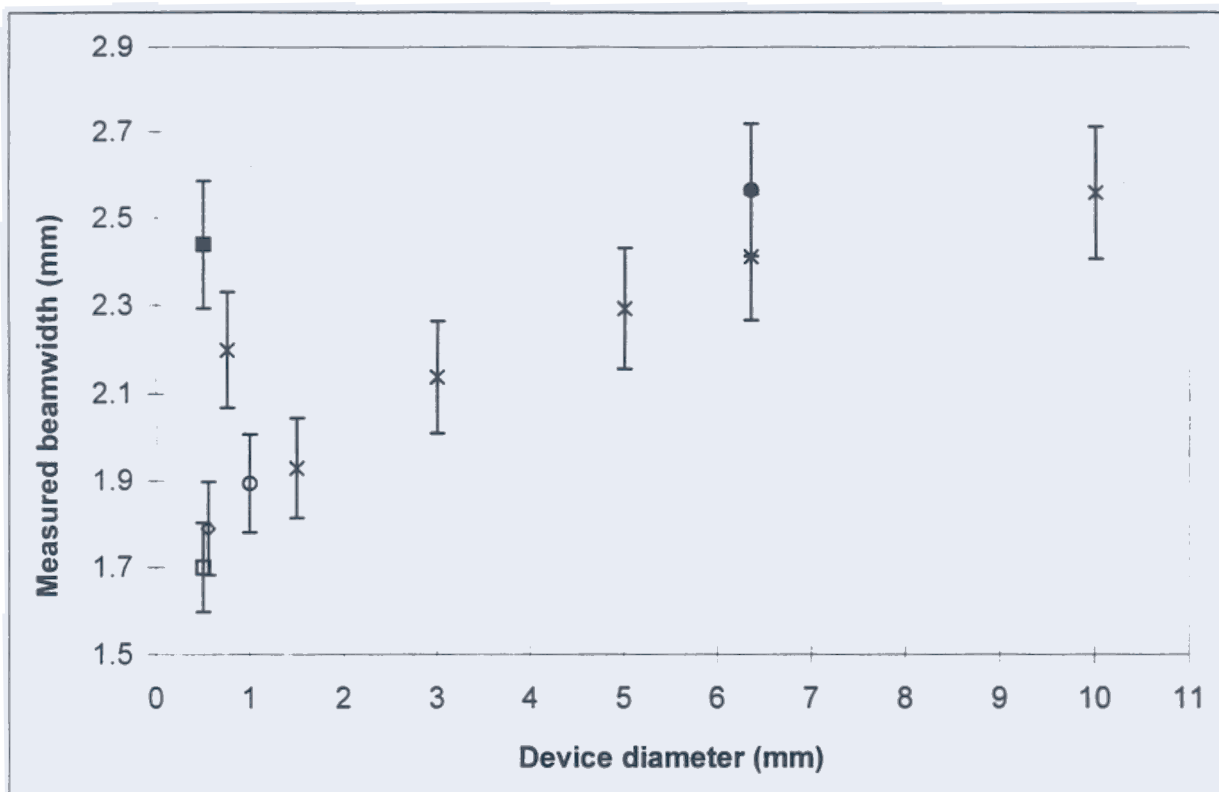


□ 0.5 mm hydrophone; * 1 mm hydrophone; o 1 mm disc

Figure 7.5: Beamplot data for 2.5 MHz focused transducer (F01951173), crystal diameter 10 mm (recorded at 50 mm separation distance). Bandwidth limited to 4.5 MHz. All values are derived from measurements made using ball pulse-echo targets unless stated. Error bars ($\pm 6\%$) are estimates, based on repeatability and symmetry

Again, it appears that for this transducer, there is an increasing trend in measured beamwidth as a function of ball target size, the increase being 10% up to the largest transducer used, indicating that spatial-averaging is becoming more significant for larger targets. However, the agreement between the hydrophone data and the disc pulse-echo target is excellent: the values obtained with these devices differ from the ball targets by approximately 10%. This may tentatively indicate that a disc pulse-echo target is more appropriate for measuring the beamwidth of focused transducers. The smallest diameter ball target (0.76 mm) produces the best agreement with the hydrophone and disc target values (7%).

Given the much improved agreement in measured beamwidths seen for this 2.5 MHz case, this reinforces the view that the lack of agreement seen with the 1.0 MHz transducer may be due to the contributions made by the higher frequency components to the measured beamwidths.



□ 0.5 mm hydrophone; ■ low pass filtered 0.5 mm hydrophone; ◇ 0.56 mm disc; ○ 1 mm disc; • low pass filtered 6.35 mm ball target

Figure 7.6: Beamplot data for 5 MHz focused transducer (F01951170), crystal diameter 10 mm (recorded at 50 mm separation distance). All values are derived from measurements made using ball pulse-echo targets unless otherwise stated. Error bars ($\pm 6\%$) are estimates, based on repeatability and asymmetry

The results shown in Figure 7.6 for the 5 MHz case show a similar trend to the 2.5 MHz data, with spatial-averaging effects becoming more significant for the larger ball targets, although measurements made using the 0.76 mm ball target produced a -6 dB beamwidth larger than expected. However, this may be attributable to the mounting configuration, as the 0.76 mm target was realised by a commercially-available stylus, which had a comparatively large support. This may have caused erroneous signals to be present in the acquisition window. For such a small target, the transducer edge-wave (see Appendix D) is more likely to be reflected from the ball mount when the target is moved off axis: this will have the effect of increasing the measured beamwidth. The other targets used were sufficiently large such that the mounting posts employed had a much smaller contact area with the ball target.

The majority of the results shown for the 5 MHz transducer were not derived from filtered data, and the results shown in Figure 7.6 illustrate the significant effect that filtering has on the derived beamwidths. At first sight, the results again indicate an increase in the measured beamwidth for the larger pulse-echo targets of approximately 30% over the range of target dimensions studied.

The different filtering conditions used, however, can mask the actual trends. As has been previously discussed, stipulating the use of identical filtering conditions to be applied to all forms of pulse-echo and hydrophone measurements, in order that the -3 dB hydrophone and -6 dB pulse-echo beamwidths are equivalent is a highly idealised situation. It can be seen here that limiting the bandwidth of the hydrophone acquisition system to 6 MHz produces a 3 dB beamwidth of 2.44 mm, compared with 1.7 mm found for the wide bandwidth case. However, this agrees more readily with the -6 dB beamwidth values found using the larger ball pulse-echo targets. Further, measurements were made on the 6.35 mm diameter ball target, and the values of the beamwidths found in the filtered and unfiltered cases agreed to 6%, although the filtered results were slightly higher.

Looking in more detail at the frequency content of the pulse-echo waveforms reveals the possible influence of the higher harmonics on the measured beamwidths. The higher harmonics of the fundamental frequency possess progressively smaller beamwidths and so whether or not they are present in the receive response of the transducer will directly affect the beamwidth measurement. In fact, the second harmonic may be observed in the pulse-echo response of all of the small targets used. Taking the larger diameter ball targets, the relative magnitude of the second harmonic component in relation to the fundamental level for the 3 mm, 5 mm, 6.35 mm and 10 mm diameter balls are respectively 53%, 56%, 53% and 53% indicating an independence with ball diameter. In contrast, the second harmonic level for the 1.5 mm diameter ball target is 78%. It is interesting also to note that, for pulse-echo measurements made using the 0.56 mm disc target, the second harmonic is 73%. This may partly explain the significantly smaller beamwidths obtained using the smaller pulse-echo targets. This trend occurs because for larger targets, significant spatial-averaging of the second harmonic occurs in the pulse-echo response. For the 3 mm diameter disc, the second harmonic level produced was 35%.

As with the unfocused transducers, a larger disc pulse-echo target was used with the 5 MHz focused transducer for beam profiling: in this case, a 3 mm disc produced a measured beamwidth of 3.0 mm. It is instructive to compare this to the spatial-averaging conditions derived for the unfocused case. If we take our "true" beamwidth as 2.44 mm in this case, and our disc diameter as 3 mm, we would expect that our measured beamwidth to be approximately 10% greater than the true beamwidth, whereas in fact, the difference is 23%. This shows that spatial-averaging effects using disc targets may be significantly worse for focused fields.

7.4 CONCLUSIONS

The measurements reported in this Section have been used to derive the requirements and protocol embodied in the draft Part 2: Calibration Procedure. Specifically, the findings are as follows:-

- in any measurement situation, the smallest available hydrophone or pulse-echo target should be used which produces sufficient signal-to-noise;
- the use of ball pulse-echo targets in the cross-axial beam profiling of unfocused transducers has been shown to produce good agreement with data derived from hydrophone measurements, with results compared at the -6 dB and -3 dB levels respectively;
- the use of disc pulse-echo targets has also produced beamwidth data which agrees well with reference hydrophone information;

- the models derived in Appendix E for estimating the extent of spatial-averaging for the disc and ball target cases can be appropriately applied to unfocused transducers;
- pulse-echo beam profiling measurements made on focused transducers have tentatively shown that spatial-averaging is more prevalent for ball targets than was seen for unfocused transducers, thereby restricting the range of target sizes that may be used. It should be noted, however, that the effect was of the order of 10%, even for situations in which the ball target diameter was five times the -6 dB pulse-echo beamwidth;
- disc pulse-echo targets used for profiling focused transducers have produced data which agrees well with hydrophone measurements;
- to get the best agreement between pulse-echo and hydrophone data, identical filtering needs to be applied in each case. However, if such filtering is not available, using the drive system at the lowest amplitude setting (and thereby restricting the extent of nonlinear propagation) will produce data which is comparable to the true, hydrophone-derived beamwidth;
- in the case of hydrophone measurements, where nonlinear propagation produces higher harmonics of narrower beamwidth, the filtering applied should be such as to ensure that the level of second and higher harmonics in the acoustic waveform is less than -20 dB.

7.5 RECOMMENDATIONS

To obtain beamwidth data which agrees with reference data to within 10%, the following recommendations should be followed for selecting target size:

For unfocused transducers:

If a disc pulse-echo target is used, its diameter should not exceed $0.27 * a_t$, where a_t is the radius of the transducer crystal;

If a ball pulse-echo target is used, its diameter should not exceed $0.1 Y_0$. This should not be used for profiling measurements in the transducer near-field.

For focused transducers:

If a disc pulse-echo target is used, its diameter should not exceed 0.5 times the -6 dB pulse-echo beamwidth;

If a ball pulse-echo target is used, its diameter should not exceed 3 times the -6 dB pulse-echo beamwidth. Further, the dimensions of the mounting post relative to the ball diameter shall be sufficiently small such that no erroneous signals can be seen in the acquisition window. Note that a factor of 3 has been used in the Part 2: Calibration Procedure. Consideration should be given to reduce this to a factor of 1.5 to 2.

8 COLLIMATORS

As part of the initial stage of the project, questionnaires were despatched by NPL-CMMT to members of the IAG, requesting information on C-scan procedures and general shop-floor practice. The responses to these indicated a high percentage of users applied collimators in their C-scanning work. Although brass was sometimes used, "to increase the penetrative power of the ultrasound", the majority used collimators fabricated from PTFE as a means of increasing spatial resolution. Use of PTFE in this application arises due to its high ultrasonic attenuation and because its acoustic impedance is reasonably well matched to that of water.

Although widely used, there is a lack of understanding regarding the way in which the collimator alters the properties of the acoustic field, and because of this, it is not currently possible to predict the effects attributable to a particular collimator geometry. The aim of this part of the project was to carry out a systematic study of how the collimator modifies the characteristics of the ultrasonic field. The work was targeted towards producing requirements and recommendations for the Part 1: Operational Procedure, the aim being to specify the collimator geometry in any particular application which enables the properties of the field to be altered in a deterministic manner.

8.1 SPECIFICATION

Discussion with NPL-CMMT led to a general configuration of the collimators being decided upon, and a final design specification was agreed with NPL Engineering Services. This is shown in Figure 8.1. A series of different devices were made using PTFE, with variations in two main attributes: the collimator thickness (1, 2, 4, 8 and 12 mm), and the aperture diameter (2, 4, 6 and 8 mm). In addition, a stainless steel collar was made that could sit around the transducer casing, enabling variation of the stand-off distance between the back face of the collimator and the transducer crystal, over a range of a few mm. After the first set of collimators were made, it was found that having only two fixing screws meant that the device was not always secure on the front face of the transducer: subsequent configurations employed three fixing screws instead.

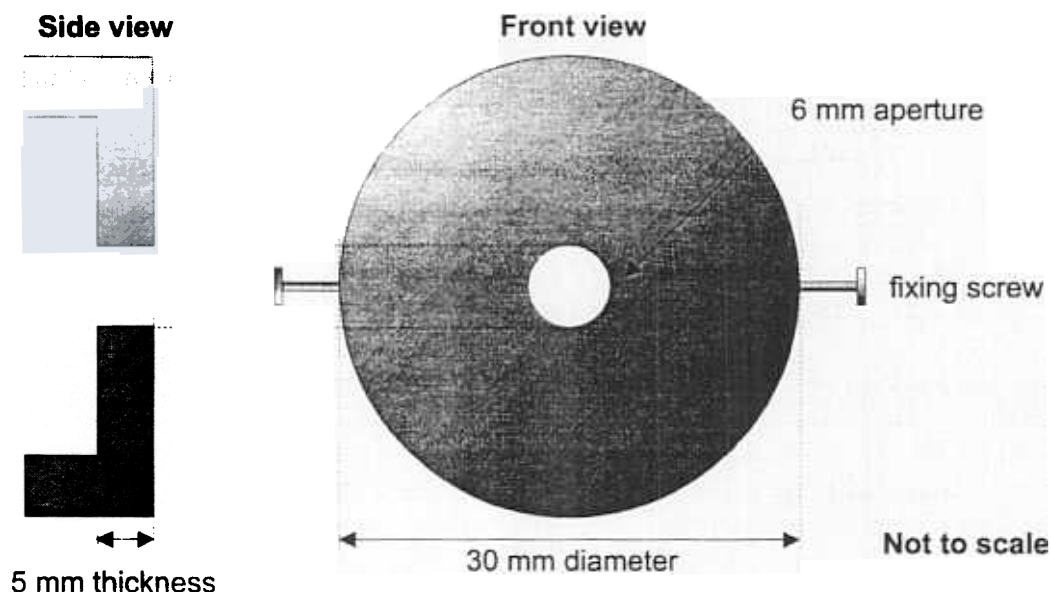


Figure 8.1: Example of collimator specification used

Using the drive unit and a selection of unfocused transducers described in Section 3.3, the variation in collimated beam parameters was investigated for each of the collimator attributes detailed in Sections 8.3 to 8.6 below. Additionally, this provided data for use by NPL-CMMT to carry out prescribed C-scans which itself fed into providing information for the Part 2: Operational Procedure.

8.2 THEORY

It is anticipated that the effect of placing a collimator on a transducer will be to create a transducer whose aperture is equal to the diameter of the collimator. Consequently, the expressions given in Appendix D for the behaviour of an unfocused field should provide the basis for testing this hypothesis. Of particular importance in the context of understanding the collimation effect is the plane and edge-wave concept described in Appendix C.

8.3 SET UP AND INITIAL INVESTIGATIONS

The same procedure described previously (Section 6.2) was employed for system set-up and alignment. A series of initial investigations was carried out, to assess the change in the acoustic waveform produced when the collimator was attached, and to gauge an initial idea of the effect of the collimator on the position of the last axial maximum, Y_{0+} , and the measured -6 dB beamwidth. These measurements were undertaken on the 10 mm diameter unfocused transducer (F1655), operating at nominally 2.5 MHz and used a collimator of aperture diameter 8 mm and thickness 5 mm, mounted flush with the transducer face. The acoustic waveforms measured using a hydrophone at separation distance of 0.9 mm from the front of the collimator, over a variety of cross-axial positions can be seen in Figures 8.2 to 8.4.

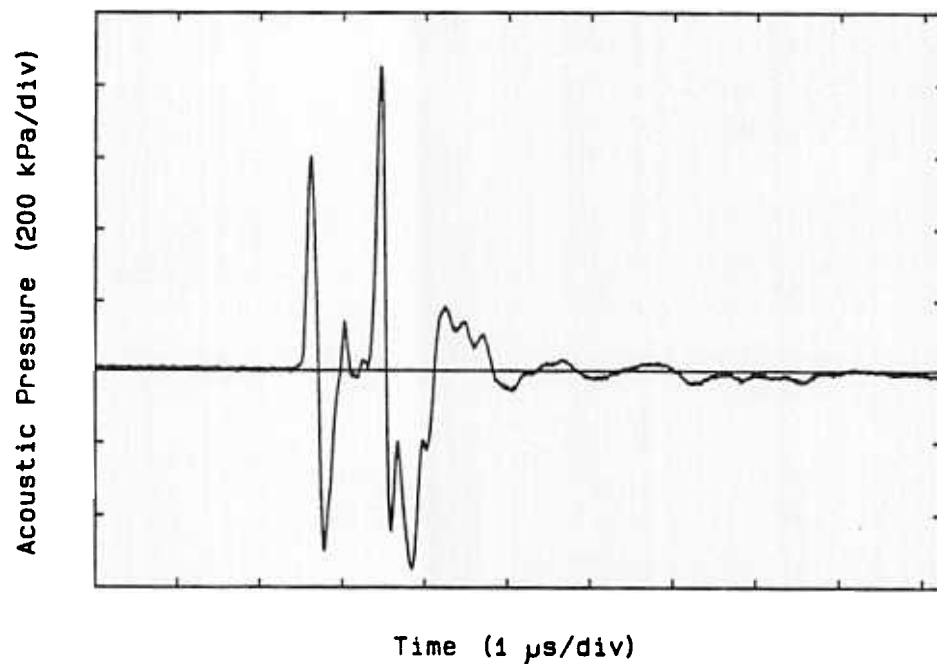


Figure 8.2: Acoustic waveform acquired at 5.9 mm from transducer F1655 with 8 mm diameter collimator

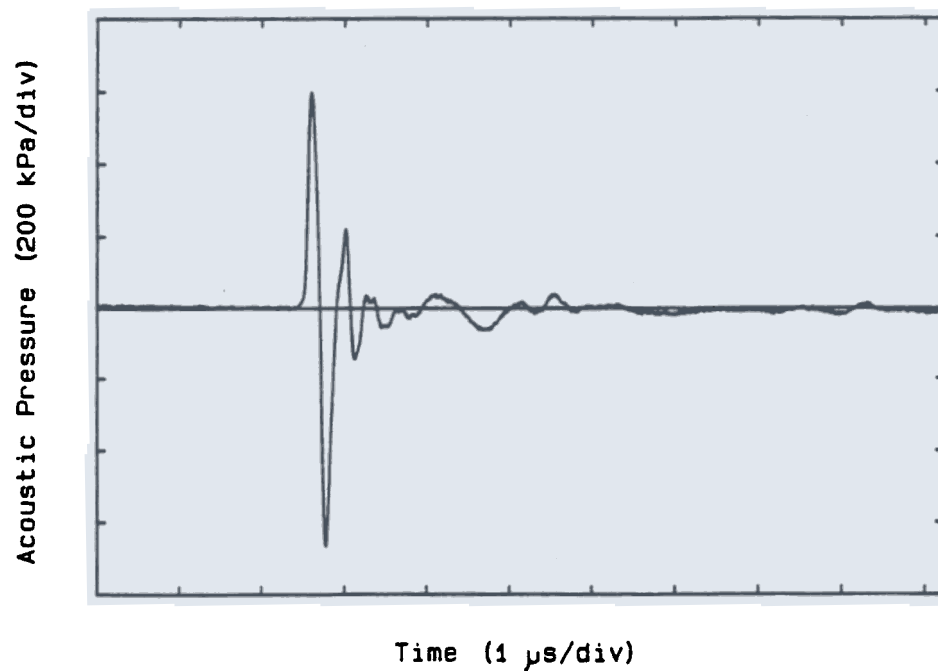


Figure 8.3: Acoustic waveform acquired at 5.9 mm from transducer F1655 with 8 mm diameter collimator, 2 mm off-axis (positive direction)

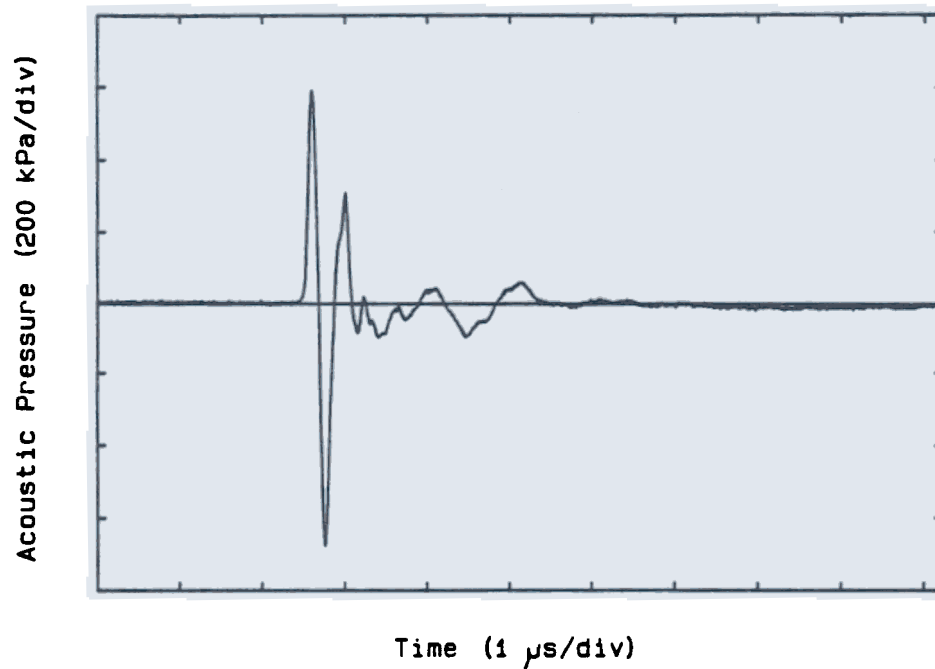


Figure 8.4: Acoustic waveform acquired at 5.9 mm from transducer F1655 with 8 mm diameter collimator, 2 mm off-axis (negative direction)

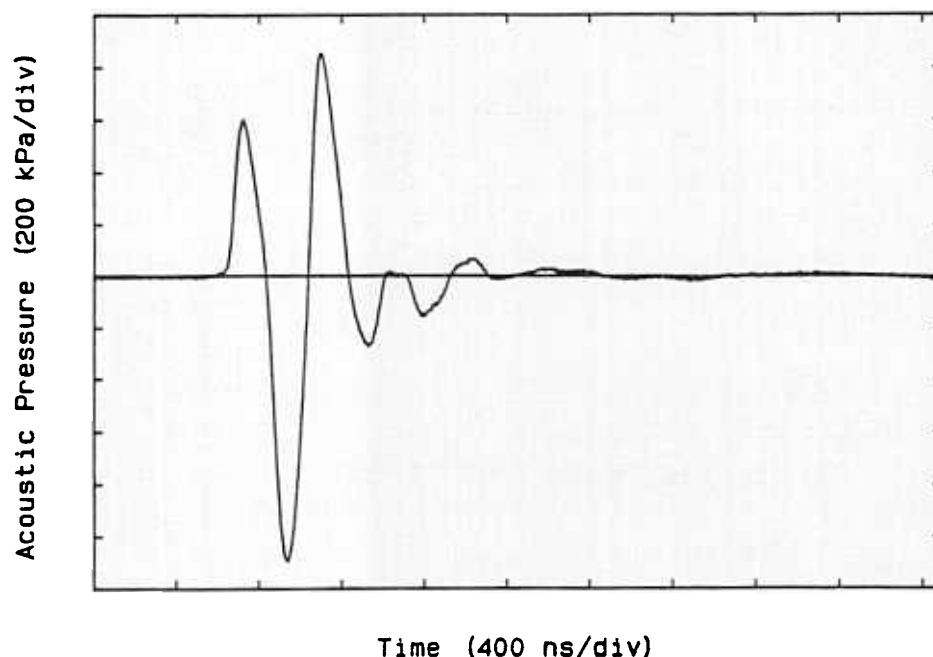


Figure 8.5: Acoustic waveform acquired at the modified last-axial maximum of transducer F1655 with 8 mm diameter collimator

Note the distinct difference between the waveforms acquired at the centre of the aperture (8.2) and those acquired at the position where the edge-wave component was minimised (8.3 and 8.4) - these waveforms were acquired towards the edge of the aperture. Figure 8.5 shows the acoustic waveform at the modified Y_{0+} , 25.5 mm (see below).

The fine structure close to the transducer face is reflected in the cross-axial beamplot made at 0.9 mm, Figure 8.6. Piston theory predicts a “top-hat” distribution for the cross-axial beam profile at the transducer face. The behaviour demonstrated arises due to the interaction between the plane-wave component and the edge-wave component originating from periphery of the collimator. Only on the axis does the edge-wave arrive coherently. Any inconsistencies in manufacture (e.g. non-circularity) would also contribute to the irregular nature of the field. Figures 8.7 to 8.8 show the trend in measured -6 dB beamwidth as a function of axial separation, illustrating the small variation in the field beamwidth (the beamwidth at the Y_{0+} position, 25.5 mm is 3.48 mm).

The last axial maximum (Y_{0+}) for this transducer when uncollimated had been found at 38 mm from the transducer face (see Appendix A). Attaching the collimator reduced this to 20.5 mm, measured from the output face of the collimator. When the thickness of the collimator is taken into account, this produces a new Y_{0+} value of 25.5 mm, which agrees well with the approximate value of 26 mm predicted by plane-piston theory when the collimator aperture radius is substituted for the transducer crystal radius in the calculation of a^2/λ . It also shows that the back surface of the collimator (the surface nearest to the transducer) appears to define the aperture through which the ultrasound is emitted, as one would expect.

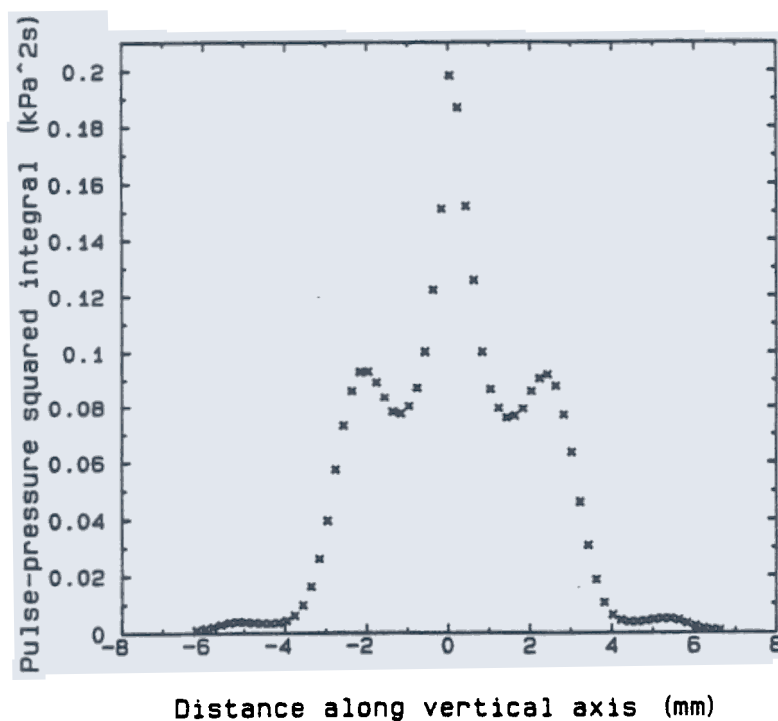


Figure 8.6: Beamplot at 5.9 mm (from transducer), 2.5 MHz transducer F1655 with 8 mm collimator

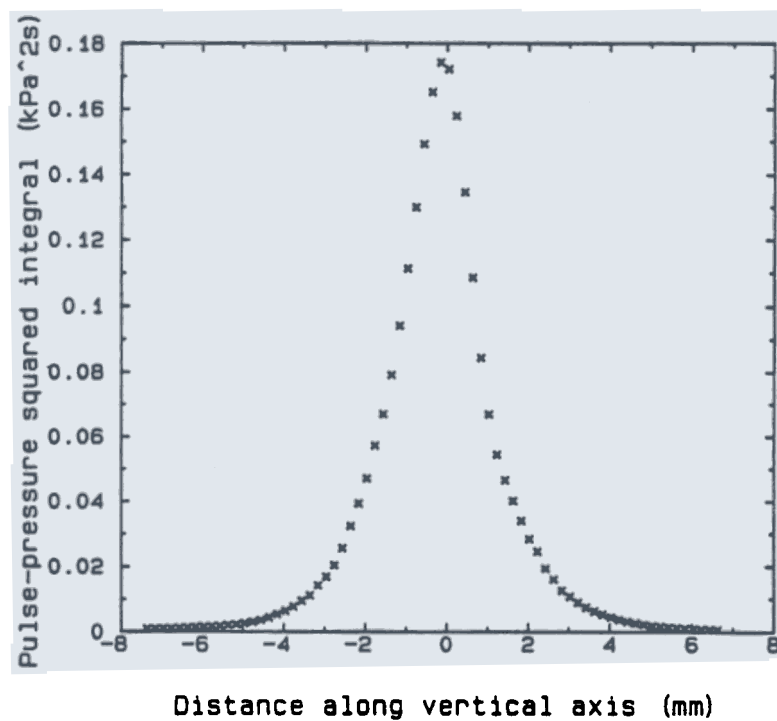


Figure 8.7: Beamplot at 20.5 mm (from transducer), 2.5 MHz transducer F1655 with 8 mm collimator

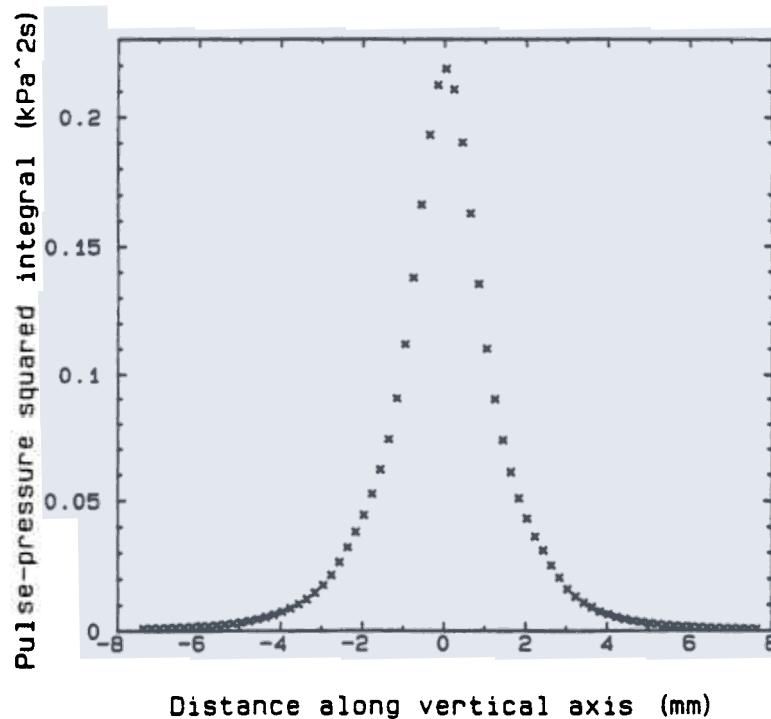


Figure 8.8: Beamplot at 25.5 mm (from transducer), 2.5 MHz transducer F1655 with 8 mm collimator

After these initial measurements, a series of systematic investigations were carried out to assess the:

- a) effect of changing collimator aperture size;
- b) effect of changing collimator thickness;
- c) effect of changing collimator-transducer stand-off distance;
- d) dependence of the cross-axial beam profile with variation in axial separation.

8.4 INVESTIGATION OF EFFECT OF COLLIMATOR APERTURE DIAMETER

8.4.1 Experimental set up

The study was carried out to establish whether there were any simple rules which could be applied to predicting collimator-modified values of Y_{0+} which could then be employed in the setting up of a C-scan. A 10 MHz transducer was used for this investigation, the drive unit output setting being the high frequency band (10 - 30 MHz). The lower acoustic pressures produced using the high band setting reduced the extent of nonlinear propagation in the water path. The bandwidth of the hydrophone and amplifier system used was limited to 25 MHz, to further reduce effects attributable to harmonic components in the pulse. Four different collimators were used, each of thickness 5 mm, with aperture diameters 2, 4, 6, and 8 mm. For each collimator, axial scans were performed using hydrophones to determine the collimator-modified Y_{0+} position. In each case, the acoustic signal was remaximised cross-axially and acquired at the new Y_{0+} position. In addition, the acoustic waveform was acquired just outside the face of the collimator, on the beam axis at a distance of 6 mm from the transducer face.

8.4.2 Results

The axial response for the pulse pressure-squared integral (*ppsi*) derived from an 8 mm diameter collimator is shown in Figure 8.9. This shows a peak in *ppsi* at around 60 mm (relative to the collimator, 65 mm relative to the transducer) - the uncollimated case produced a *ppsi* Y_{0+} of 140 mm. The full results are summarised in Table 8.1.

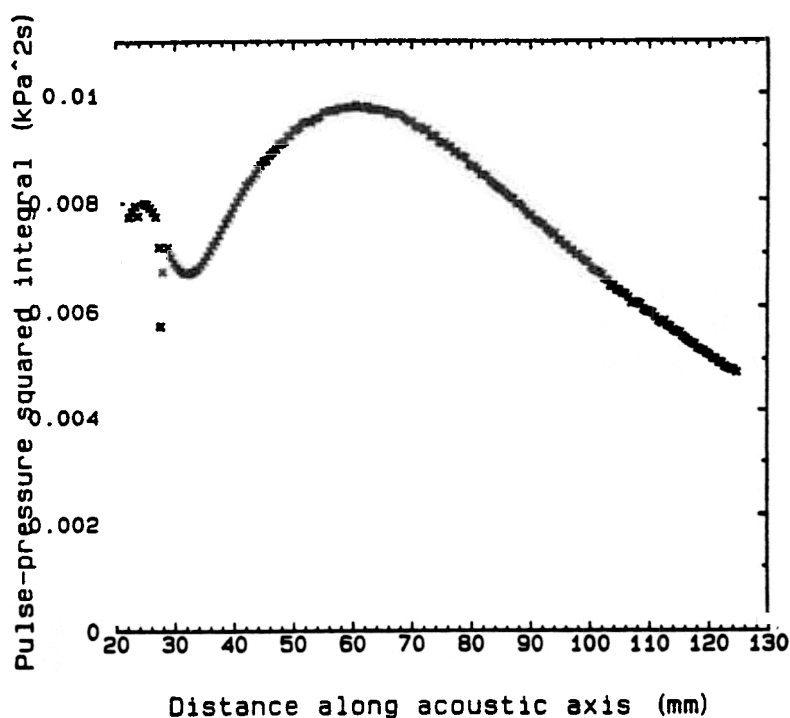


Figure 8.9: On axis variation of pulse pressure-squared integral, for the 10 MHz transducer F1658 fitted with 8 mm diameter PTFE collimator.

Table 8.1: Summary of Y_{0+} values for the 10 MHz transducer and 4 collimators of various diameters. Uncollimated parameters are provided for comparison.

Collimator aperture diameter (mm)	Y_{0+} , relative to transducer face (mm) <i>parameter</i>			Frequency in Y_{0+} plane (MHz)	Predicted Y_{0+} from f in plane (mm)	Predicted Y_{0+} from f at face (mm)
	p^+	p^-	<i>ppsi</i>			
2	15	9.5	10	8.004	5.4	5.4
4	20	30	20.5	7.448	20.1	21.6
6	41	54	41	7.337	44.5	48.5
8	71	87	65	6.915	74.6	86.3
uncoll	165	125	140	7.116	120	135

The first point to note is the expected shift in position of the on-axis maximum as a function of collimator aperture diameter. Second, despite the limited system bandwidth, there are still some differences in the maximum positions depending on the parameter under consideration. Third, the measured frequency at the modified Y_{0+} found using the pulse

pressure-squared integral in each case also decreases as a function of aperture diameter. This is almost certainly illustrative of the frequency downshift described by ASTM E 1065-92 and the Panametrics document. This leads to an increasing discrepancy between the measured and predicted values of Y_{0+} , depending on which frequency value is used in to derive the wavelength in a calculation of a^2/λ . This provides additional evidence to suggest that for high frequency transducers, the frequency spectrum should be captured at a position as close to the transducer as possible, to minimise the effects of downshift.

When the frequency as measured in the plane of maximum $ppsi$ is considered, the best agreement between theory and experimental data appears to be in p_+ , although the 2 mm collimator measured value differs from theory by a significant amount in all cases. Note that the thickness to aperture diameter ratio (see Section 8.5) was 2.5 in this case, which was outside the range investigated below, and hence may cast doubt on the validity of the data.

8.5 INVESTIGATION OF EFFECT OF COLLIMATOR THICKNESS

The drive behind this particular investigation was a discussion with a member of the IAG, who provided a rule of thumb governing optimum values of the ratio of the collimator thickness to the diameter (the ratio should lie in the approximate range 0.6 to 1.4). To test out the variation in effects on the acoustic field over such a range, a series of collimators were fabricated so that this ratio lay in the range 0.21 to 2. A 5 MHz transducer of crystal diameter 10 mm was used, in conjunction with collimators of thickness 1.26, 1.93, 4.88, 7.95 and 11.95 mm, all being of diameter 6 mm. The hydrophone employed was a 0.5 mm bilaminar membrane device, with an amplifier which produced a system bandwidth of approximately 50 MHz. Reference data had been obtained previously on this (uncollimated) transducer using a different hydrophone-amplifier combination: agreement between the two data sets was around 10%.

The experimental set up was the same as that described in Section 8.2, with the collimators being attached to the transducer underwater as required. In all cases, after alignment, the hydrophone was brought close to the face of the collimator to perform a scan of the axial response which determined the position of Y_{0+} . At the Y_{0+} position, a cross-axial beamplot was performed, and the acoustic waveform captured. The data produced is displayed in Table 8.2.

Table 8.2: Summary of measurements undertaken to investigate the influence of collimator thickness on the properties of the acoustic field for a collimator of diameter 6 mm.

Collimator thickness (mm)	Ratio of collimator thickness to aperture	Y_{0+} in $ppsi$ (to collimator) (mm)	Y_{0+} $ppsi$ relative to transducer (mm)	-3 dB beamwidth in $ppsi$ at Y_{0+} (mm)	p_+ at centre of plot, at Y_{0+} (MPa)
uncoll	-	-	59	2.40	3.8
1.26	0.21	30	31	1.33	3.84
1.93	0.32	33	35	1.63	4.12
4.88	0.81	23	28	1.23	3.64
7.95	1.33	22	30	1.30	4.48
11.95	1.99	18	30	1.13	4.49

With the exception of the 1.93 mm thick collimator, there is excellent agreement between the Y_{0+} positions found. Inspection of the axial plot for the 1.93 mm collimator case shows a degree of uncertainty in the position of the maximum, which may have been due to system misalignment, or trigger instability. The difference in the -3 dB beamwidth for this collimator when compared to the others may also indicate that the true Y_{0+} position was not found. Hence, it would appear that the effect of the collimator thickness on the beam pattern produced is minimal, with two provisos:

- a) the collimator thickness and aperture diameter should be such that the modified Y_{0+} position is outside the aperture;
- b) the material from which the collimator is made should be thick enough to ensure that it attenuates all of the ultrasound emitted from the crystal that is being masked and this will depend on the frequency of operation.

8.6 INVESTIGATION OF EFFECT OF VARYING STAND-OFF DISTANCE

8.6.1 Experimental set up

A 2.5 MHz transducer was used in conjunction with an 8 mm diameter collimator of thickness 5 mm and a stainless steel collar. Use of the collar enabled a variation of around 5 mm in the stand-off distance: the limiting factor in this case was the positioning of the fixing screws on the collimator itself, as the distance between the centre of these holes and the back face of the collimator was around 4.5 mm. Figure 8.10 illustrates the configuration. Care was taken during setting up to ensure that the gap between the transducer and the back of the collimator was filled with water: this was done by attaching the collimator underwater and tilting the transducer mount after attachment so that any bubbles present could escape through the aperture.

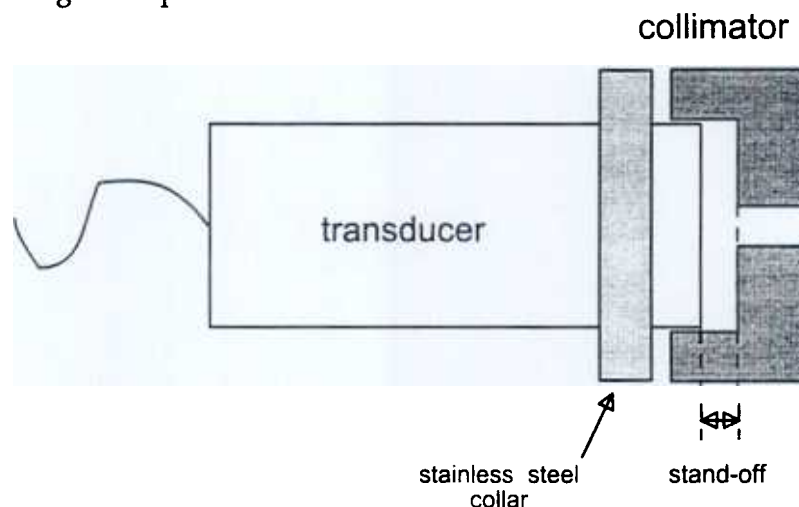


Figure 8.10: Schematic diagram of configuration used to investigate the effect of stand-off distance

Measurements were made using stand-off distances of 0 and 3 mm: in each case, a series of 3 waveforms were acquired with a hydrophone located 1 mm away from the aperture, as a function of cross-axial distance (on-axis, and ~4 mm off axis, in the horizontal plane). The contributions from edge and plane-waves were easily identifiable at the 3 positions: interestingly, on the axis, the centre frequency was calculated at 1.15 MHz, almost certainly

due to the destructive interference between the two components. For each of the stand-off distances, an axial scan was performed to ascertain the modified Y_{0+} position, and a pair of cross-axial beamplots were made at this maximum.

Waveforms were also acquired at the 1 mm position using a 1 mm stand-off distance: however, these were almost identical to those seen with the collimator mounted flush with the face, and given that there was very little variation shown in the position of Y_{0+} when measurements were made at the two extreme stand-off positions, it was assumed that this "middle" stand-off position would be similarly invariant.

8.6.2 Results

The results of these measurements are summarised in Table 8.3. From these, it was concluded that varying the stand-off distance between the back of the collimator and the transducer crystal has no systematic effect. However, care should be taken to ensure that the crystal and the collimator are mounted in a parallel fashion and that the gap between the two is water filled.

Table 8.3: Summary of measured Y_{0+} and -3 dB beamwidths derived from an investigation of the effect of varying the transducer-collimator stand-off distance

Stand-off distance (mm)	Y_{0+} position (mm) (parameter)			-3 dB beamwidths in $ppsi$ (mm)	Centre frequency (MHz)
	p_+	p_-	$ppsi$		
0	27.5	23	25.5	2.07	2.43
3	28.5	22.5	25.5	2.10	2.48
uncollimated	40	32	38	2.42	2.43

8.7 INVESTIGATION OF CROSS-AXIAL PROFILE WITH AXIAL SEPARATION

Experimental set up

A 10 MHz transducer was used, with a PTFE collimator of 4 mm diameter and 5 mm thickness mounted flush with the transducer crystal. The system was aligned after the collimator had been fitted, and an axial scan performed to establish the modified Y_{0+} position. Then, a series of cross-axial beamplots were performed at Y_{0+} and at an additional 6 positions along the acoustic axis. The acoustic waveform at each measurement position was also acquired.

Results

The results are summarised in Table 8.4 and shown graphically in Figure 8.11. There is a clear indication of "self-focusing" shown by the measurements. The nonlinear distortion present is responsible for p_+ producing the narrowest beamwidth, as expected, and the $ppsi$ data falls between the two pressure parameters in the far field. The narrowest point in the $ppsi$ data occurs at a separation of 15 mm from the transducer, and not at the Y_{0+} position as

might be expected. However, it is noticeable that the -3 dB beamwidth stays approximately constant over an extended range. Inspection of the beamplots shows that there is significant cross-axial structure in p_+ and p_- at the 15 mm separation position (similar to that described in Section 8.3), and the resulting $ppsi$ plot has a very narrow central peak, which then broadens out at distances greater than 0.8 mm off-axis. The signal level at this point (and beyond) is below the -3 dB threshold.

Table 8.4: Beamwidth data obtained at a variety of measurement positions for a 10 MHz transducer and 4 mm diameter collimator

Axial position (relative to transducer)/mm	-3 dB beamwidth (mm)		
	p_+	p_-	$ppsi$
8.0	3.16	3.14	3.19
15.0	1.91	2.97	1.02
21.5 ($\equiv Y_{0+}$)	0.50	2.51	1.25
25.0	0.54	1.93	1.27
30.0	0.55	1.55	1.27
38.0	0.65	1.59	1.25
55.0	0.95	2.07	1.59

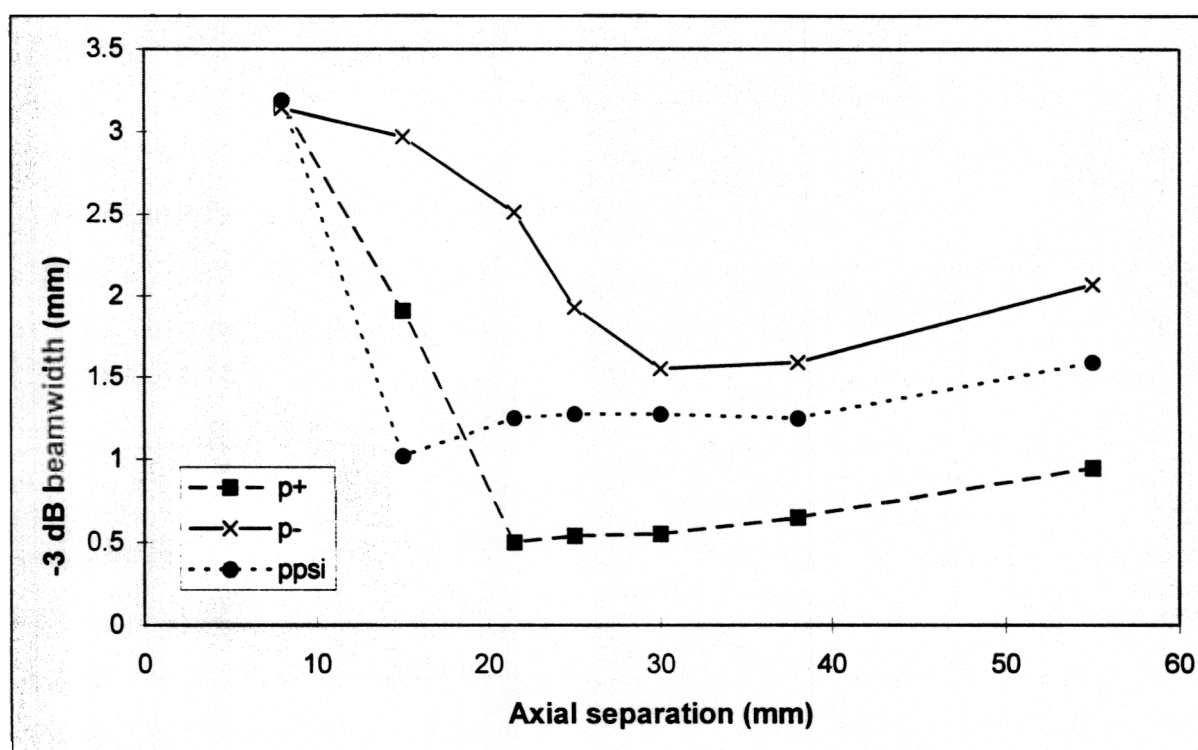


Figure 8.11: Variation in horizontal measured -3 dB beamwidth as a function of axial position determined for 10 MHz transducer F1658 and the 4 mm collimator

8.8 COMPARISON WITH THEORETICAL PREDICTIONS

Through the four principal investigations, a large amount of data was acquired from cross-axial beamplots. It is useful to compare the results obtained at the modified Y_{0+} positions in each case with the expression given in Appendix C, which gives the approximate -3 dB beamwidth from the following formula:

$$\text{-3 dB pressure beamwidth} = 0.5136 a_t,$$

where a_t is the transducer element radius. Using the collimator aperture radius for a_t will provide an indication of the extent to which collimated transducers may be considered as conventional unfocused devices, but with crystal diameters equivalent to the collimator aperture diameters. Again, the aim here is to be able to choose a particular collimator and derive a value for the spatial resolution at the modified Y_{0+} position. A comparison of the predicted and measured -3 dB beamwidths is given in Table 8.5 and shown graphically in Figure 8.12.

Table 8.5: Comparison of measurement with theory for collimated transducer beamwidths

Transducer serial number	Collimator aperture diameter (mm)	Y_{0+} position (mm)	a^2/λ prediction (mm)	Predicted -3 dB beamwidth (mm)	Measured -3 dB beamwidth (mm)
F1658	4	21.5	19	1.03	1.25
F1655	6	11	14.5	1.54	1.72
F1658	8	60	77	2.05	1.38
F1655	8	25.5	26	2.05	1.93
F11941135	6	28	29	1.54	1.23

There appears to be some scatter of data about the predicted trend, and so it is difficult to infer any systematic dependence due to the reduced size of the data set. There is perhaps an indication that the closer the measured Y_{0+} position (at which the -3 dB beamwidths were measured in each case) was to the value predicted by a^2/λ , the better the agreement between the predicted and measured -3 dB beamwidths, exemplified by F1658, which has poor Y_{0+} agreement and poor collimator resolution agreement. The measurement made with transducer F1655 (2.5 MHz) and the 8 mm collimator shows the best agreement between theory and experiment in both axial and cross-axial cases. Nevertheless the overall agreement is reasonably encouraging.

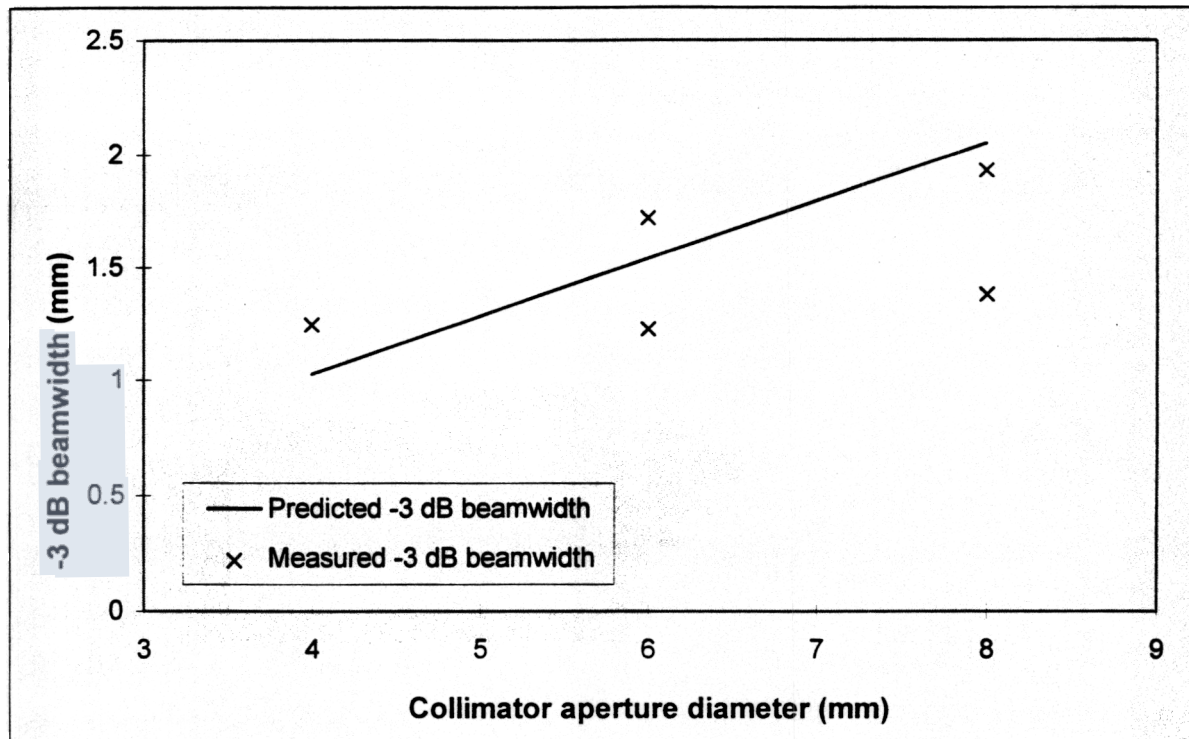


Figure 8.12: Comparison of theoretical and measured -3 dB beamwidths for various transducer-collimator combinations

8.9 CONCLUSIONS

A number of conclusions may be drawn regarding the work undertaken on collimated transducer fields:-

the investigations carried out on collimated fields have shown that in simple terms, a collimated transducer can be considered as a transducer of the same frequency, but with an aperture diameter equal to the collimator diameter. Consequently, standard relations may be used to calculate the important properties of the collimator-modified acoustic field such as the position of the last axial maximum (Y_{0+}), and the resultant beamwidths in that plane. The results may be used to define conditions for the C-scan in a systematic way such as ensuring that the panel is positioned at the last-axial maximum and potentially choosing the spatial resolution to match the specific minimum detectable defect size in any application;

- the work has also thrown light onto the requirement present in the McDonnell Douglas document that there exists minimum and maximum separations, within which collimated transducer C-scans may be made. The strong coherent structure between the plane and edge-waves components exhibited close to the transducer face is far from ideal as the quite critical alignment requirement will be impossible to maintain throughout a C-scan. At large separations the field will suffer from diffractive spreading leading to poor C-scan signal-to-noise. As a rule of thumb the collimated transducer to sample separation should perhaps lie in the range $0.7 Y_{0+}$ to $3Y_{0+}$ where Y_{0+} is the position of the last axial maximum derived from the collimator aperture;

- the effect of collimator thickness on the generated field is minimal, certainly in terms of spatial resolution, which is the primary objective when choosing to collimate a transducer. However, it appears that the ratio of the thickness to the aperture diameter should be set at 2 or less, so as not to produce data which is affected by local interference patterns possibly occurring in the aperture;
- the stand-off distance between the transducer crystal and the collimator itself produces no systematic effect on the position of the modified Y_{0+} , nor on the -3 dB beamwidth at Y_{0+} , over the small range of separations tested. These findings are of particular relevance to the operational procedure in this project: the procedures to use when measuring collimated transducer fields may be considered to be special cases of those produced for measuring unfocused transducer fields.

9 MATERIALS PROPERTY MEASUREMENTS

9.1 BACKGROUND

Throughout the project, the NPL Materials Characterisation Facility described in Section 3.2 was used to provide reference data on the ultrasonic properties of materials, ranging from the carbon-fibre composite materials used in the reference panels through to Perspex. Table 9.1 provides a compilation of the materials measured. The results of attenuation and phase velocity measurements for these materials will be summarised in Section 9.2 and described extensively in Section 9.3.

Table 9.1: Compilation of materials characterised during the project, tabulated alongside details of the specimens.

Material	Material identifier (specimen thickness)	Comments
DERA Perspex step-wedge		Measurements undertaken to provide reference values of absolute attenuation in support of DERA research
DERA reference C-scan panel		Measurements undertaken to provide reference values of attenuation to support the DERA absolute attenuation research
CMMT reference C-scan panel	FLV000	Measurements undertaken to assess the reference panel to reference panel variation in terms of their attenuation properties
Carbon-epoxy	FFD001 (10 mm) FFD002 (10 mm) FFD003 (10 mm) FFD004 (10 mm)	T300/924 unidirectional acron-epoxy FFD002: ground surface FFD001, FFD003, FFD004: surface 'as processed'
Carbon-epoxy	FGU002 (5 mm) FGU006 (5 mm) FFC009 (5 mm)	T300/924 unidirectional carbon-epoxy FFGU002: surface 'as processed' FFU006: ground surface FFC009: ground surface
Glass-epoxy	FEM002 (10 mm) FEL004 (5 mm)	Plain woven fabric, surface finish of both 'as processed'
Cloth weave	FSX000 (5 mm)	Dimensions of panel 120 mm by 140 mm, measurements undertaken to establish frequencies of ply-resonance

Table 9.2: Tabulation of acoustic property measurements for nine materials measured. Values are presented for the reflection coefficient of the water-specimen interface, the derived interfacial loss calculated from this reflection coefficient, the phase velocity for propagation of ultrasound and the bulk attenuation coefficient at two frequencies, generally 1 MHz and 5 MHz

Material	Density, ρ (g cm ⁻³)	Phase velocity at 5 MHz, (m s ⁻¹)	Reflection coefficient (from pc unless stated)	Derived interfacial loss (dB)	Attenuation coefficient (dB cm ⁻¹)		Comments
					1 MHz	5 MHz	
FFD001	1.576	3060 $\pm$ 60	0.5233	2.78	1.82	6.52	Surface as processed
FFD002	1.396	3062 $\pm$ 16	0.485	2.33	2.85	7.29	Ground surface
FFD003	1.582	3062 $\pm$ 15	0.532 0.516 (measured)	2.89	2.17	6.1	Surface as processed
FFD004	1.592	3040 $\pm$ 10	0.531 0.544 (measured)	2.88	2.27	6.31	Surface as processed
FFC009	1.569	3090 $\pm$ 40	0.518	2.71	1.824	8.20	Ground surface
FGU002	1.583	2940 $\pm$ 90	0.517	2.70	2.02	10.1	Surface as processed
FGU006	2.02	2950 $\pm$ 40	0.507	2.58	1.56	16.56	Ground surface
FEM002	1.854	2900 $\pm$ 80 (2 MHz)	0.57	3.38	4.8	39 (3 MHz)	Surface as processed
FEL004	1.869	3010 $\pm$ 70 (5 MHz)	0.58	3.61	3.6	34.5	Surface as processed

RESULTS SUMMARY

Table 9.2 presents values of the acoustic properties of the base carbon-fibre and glass-epoxy samples supplied to CMAM by CMMT during the project, giving the attenuation coefficient and phase velocity at fixed frequencies. Also presented is an averaged value of the reflection coefficient of the material surface which was determined by recording the echo strength of the water-material interface relative to a reference reflector consisting of a polished stainless-steel block of thickness 25 mm.

Unless otherwise indicated in Section 9.3, the specimens obtained from CMMT for characterisation were of dimensions 30 mm by 60 mm. Through-transmission substitution measurements were undertaken with the specimen placed as close as possible to the face of the transducer, to ensure that the effects of reflections from the specimen edges were minimal.

9.3 DETAILED MATERIALS MEASUREMENTS

Carbon-fibre reinforced polymer (CFRP) reference panels

Measurements of the transmission properties of two reference CFRP panels were made for both of the partners in the project. In the following analyses these reference panels are referred to as the DERA and CMMT (serial number FLV000) panels. Measurements were made on each of the five step sizes which were of nominal thicknesses 1 mm, 2 mm, 3 mm, 4 mm and 5 mm. As well as providing a reference characterisation for the absolute attenuation work, the comparison of measurements made on the two panels was to provide an indication of the reproducibility of the manufacturing process. An additional aim of measurements carried out on the base materials was the investigation of the effect of surface finish on acoustic property measurements. The panels were constructed with one smooth and one rough face, and the smooth surface of the reference panel was actually used for measurements.

Figures 9.1 and 9.2 give the measurements made on the DERA and CMMT reference panels respectively, for each of the steps. The results clearly illustrate a strong resonance occurring at 11.5 MHz, indicating a ply thickness of 70 μm . Measurements on the two panels were carried out independently over different time periods. Figure 9.3 gives a plot of the transmission loss (in dB) against the nominal thickness of the step for both of the reference panels at frequencies of 5 MHz and 10 MHz. The figure illustrates the good agreement between the two reference panels. Additionally, in general, the linearity of transmission loss with thickness is exceptionally good except at frequencies below 2 MHz and above 15 MHz where the signal-to-noise ratio of the acquisition system degrades, although the transmission loss values for the nominal 5 mm step are systematically lower.

Linear regressions were completed on each of the data sets at all frequencies to yield the attenuation coefficient (from the slope of the regression) and the interfacial loss (from the intercept). These quantities are respectively shown in Figures 9.4 and 9.5. Figure 9.4 gives the attenuation coefficient, expressed in $\text{dB cm}^{-1} \text{MHz}^{-1}$, derived for the two reference panels. For clarity, the error bars have been omitted from Figure 9.4, but these are typically $\pm 8\%$ for both panels and the largest component of this arises from the uncertainty in the slope derived from the linear regression. In general, with the exception of frequencies around the ply resonance, agreement is within the combined measurement uncertainties.

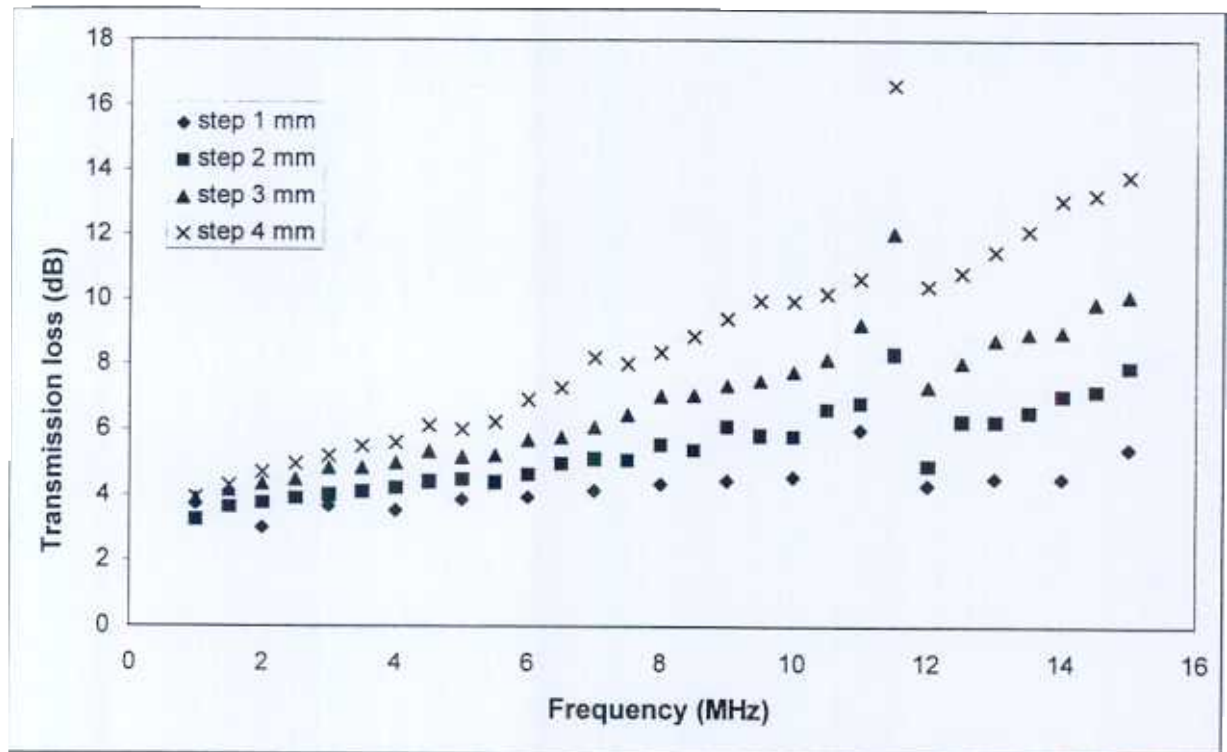


Figure 9.1: Transmission loss measurements made on DERA CFRP reference panel for the four nominal step thicknesses

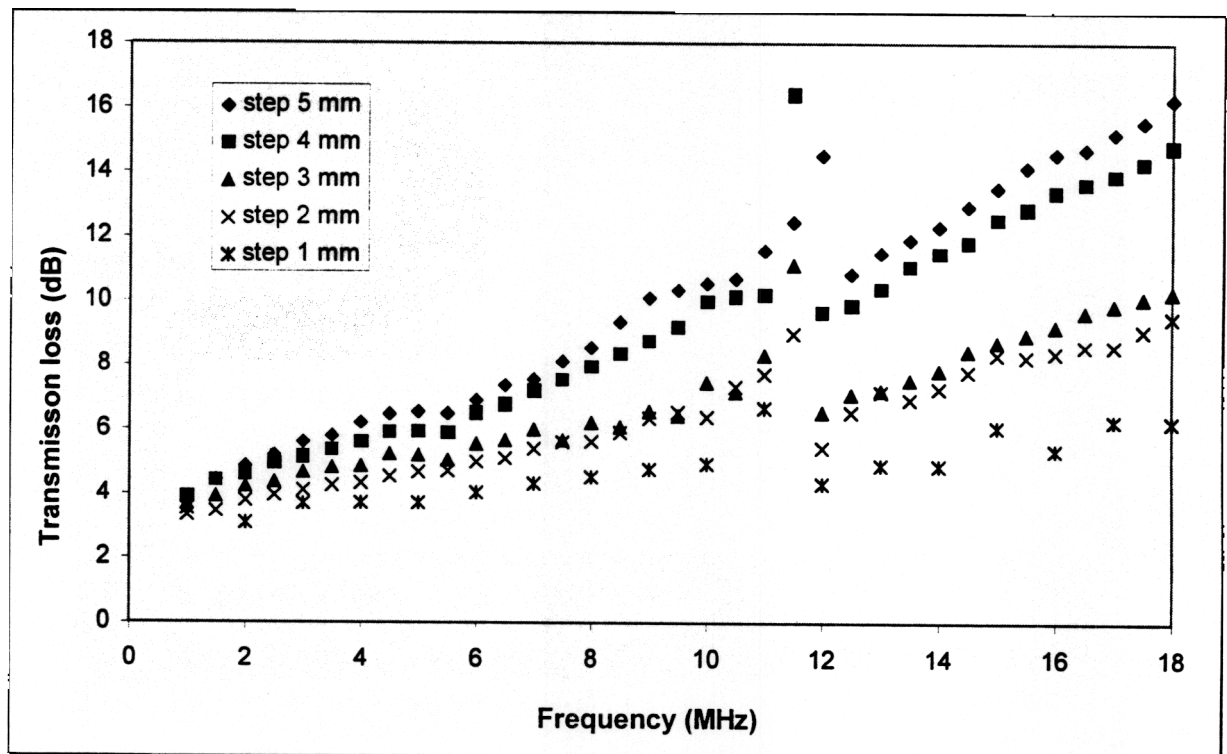


Figure 9.2: Transmission loss measurements made on CMMT CFRP (FLV000) reference panel for five nominal step thicknesses

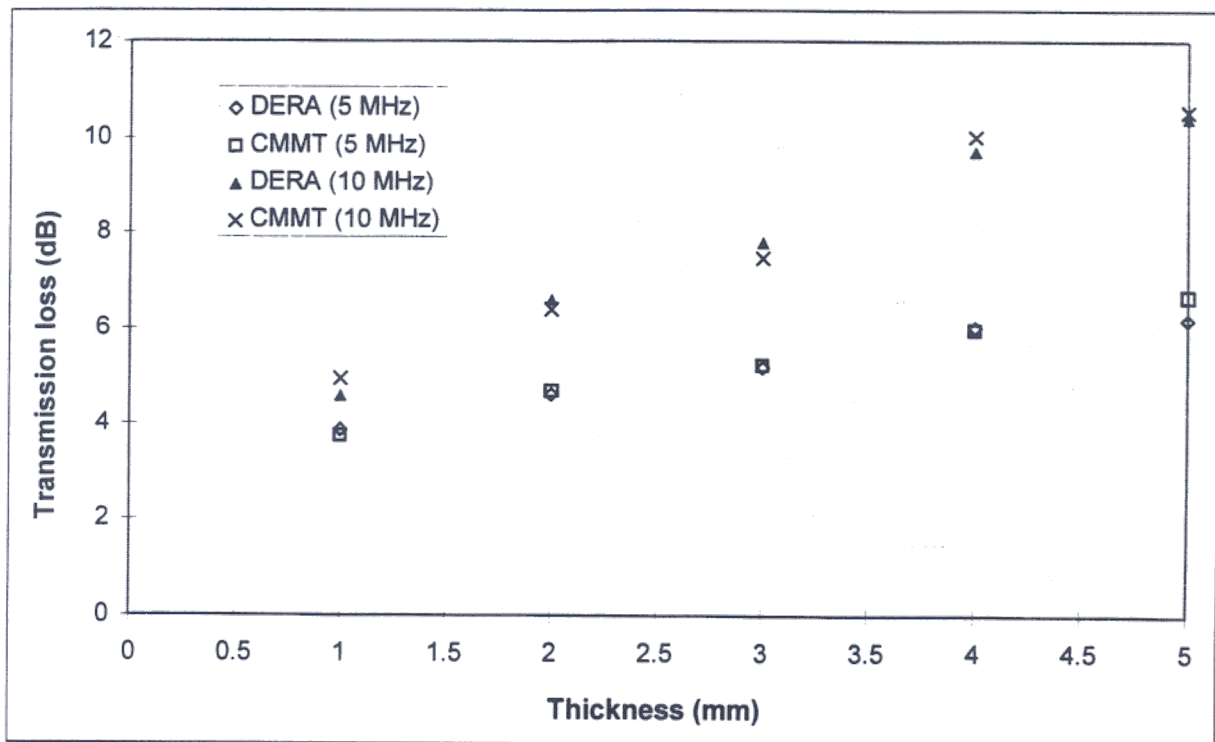


Figure 9.3: Comparison of transmission loss measurements for the two reference panels at frequencies of 5 and 10 MHz for the five nominal step thicknesses

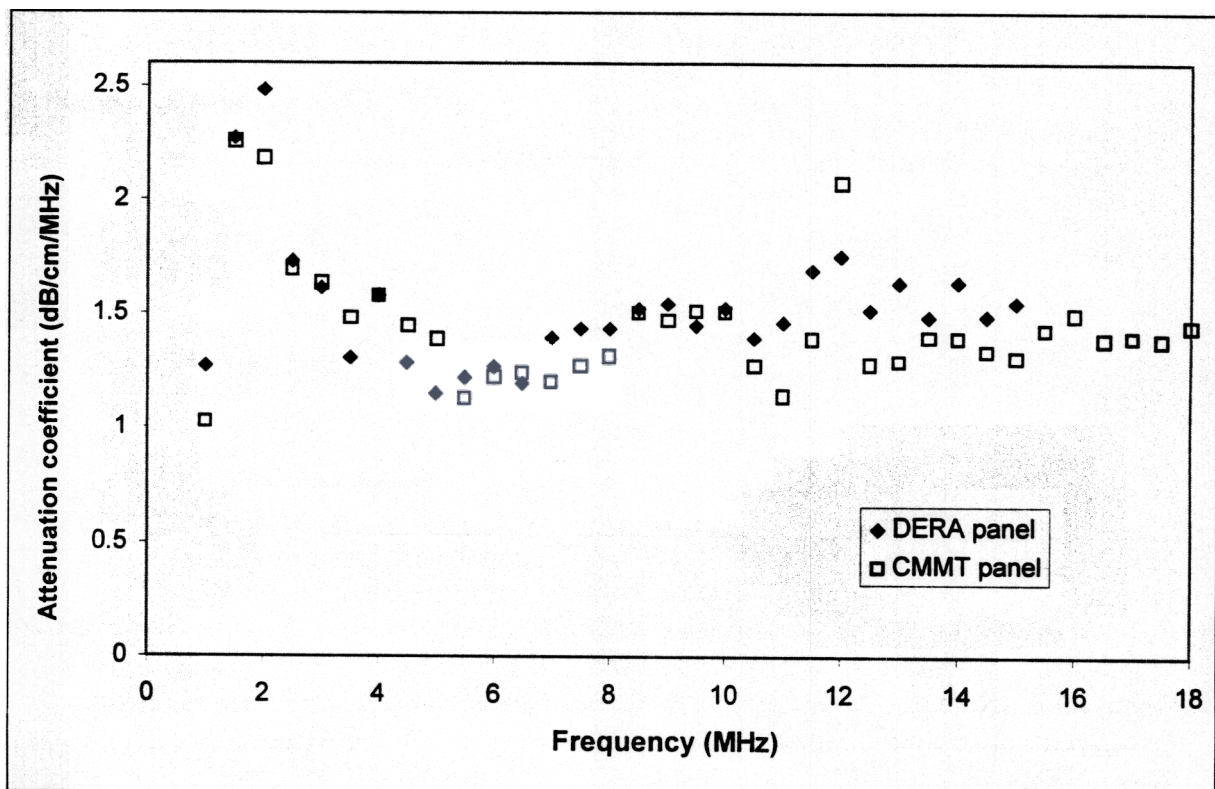


Figure 9.4: Frequency dependent attenuation coefficient of the two CFRP reference panels over the frequency range 1 to 18 MHz

Figure 9.5 gives the interfacial loss. Expanded measurement uncertainties in the intercept values are $\pm 6\%$ below 12 MHz and $\pm 12\%$ at higher frequencies. Again, agreement between the two panels is excellent, particularly below 10 MHz. Aside from the region around the ply resonance (11.5 ± 1.5 MHz) the interfacial loss up to 15 MHz for the panels is 3.3 ± 0.3 dB.

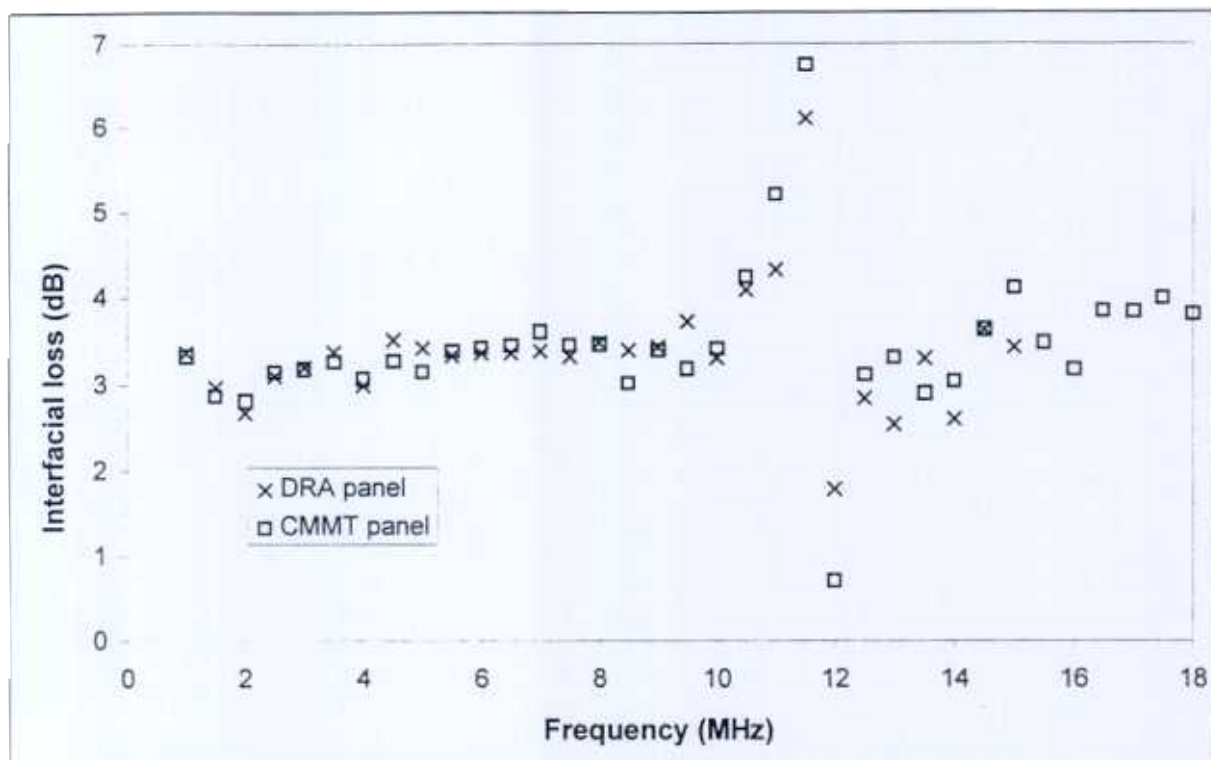


Figure 9.5: Interfacial loss in dB derived for the two CFRP reference panels

9.3.2 Carbon epoxy materials

Table 9.2 provides a list of the carbon epoxy materials characterised under this project. This sub-Section presents a compilation of the measurements.

9.3.2.1 Samples FFD001, FFD002, FFD003 and FFD004

The surface finish of the specimen FFD002 had been ground, in contrast to the remaining three samples whose finish was 'as processed'. Figure 9.6 gives the frequency dependent phase velocity of the material FFD001 over the frequency range 1 to 10 MHz. This is typical of the behaviour exhibited by all of the carbon materials studied, with a velocity dispersion of approximately 30 m s^{-1} over the frequency range of interest. For all of the carbon epoxies, the interfacial losses were derived from the acoustic impedances as calculated from the measurement data in Table 9.2 and these were then used to derive the attenuation coefficient of the material.

Figure 9.7 gives the measured attenuation coefficients for the specimens FFD001 and FFD002. The 95% confidence level random uncertainties of the two sets of attenuation coefficient values is estimated to be $\pm 3\%$, so that the differences occurring between the two data sets over the frequency range 4 to 6.5 MHz are significant. Results for the ground surface are therefore higher, presumably through increased surface losses. The ground

surface of FFD002 was appreciably rougher (over a finer textured scale) than the 'as processed' specimens and it is possible that an insufficient wetting of the surface gave rise to the higher derived attenuation coefficients.

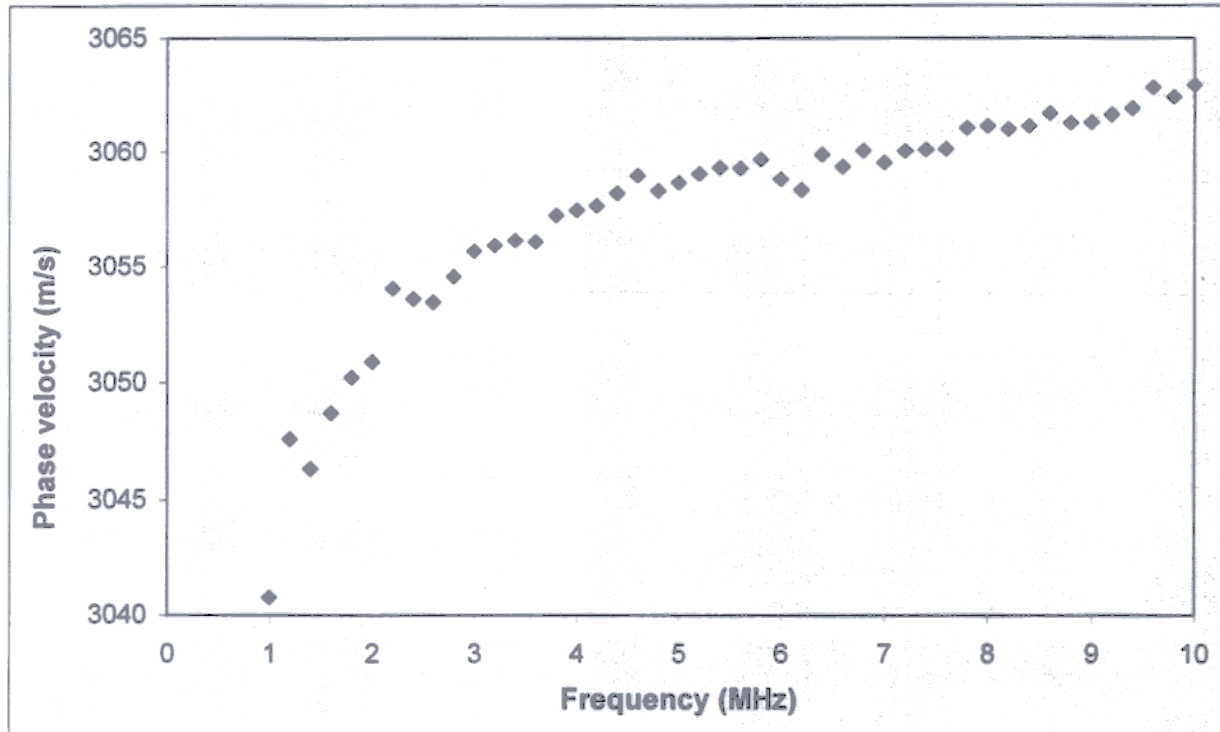


Figure 9.6: Measured frequency dependent phase velocity of the carbon epoxy sample FFD001

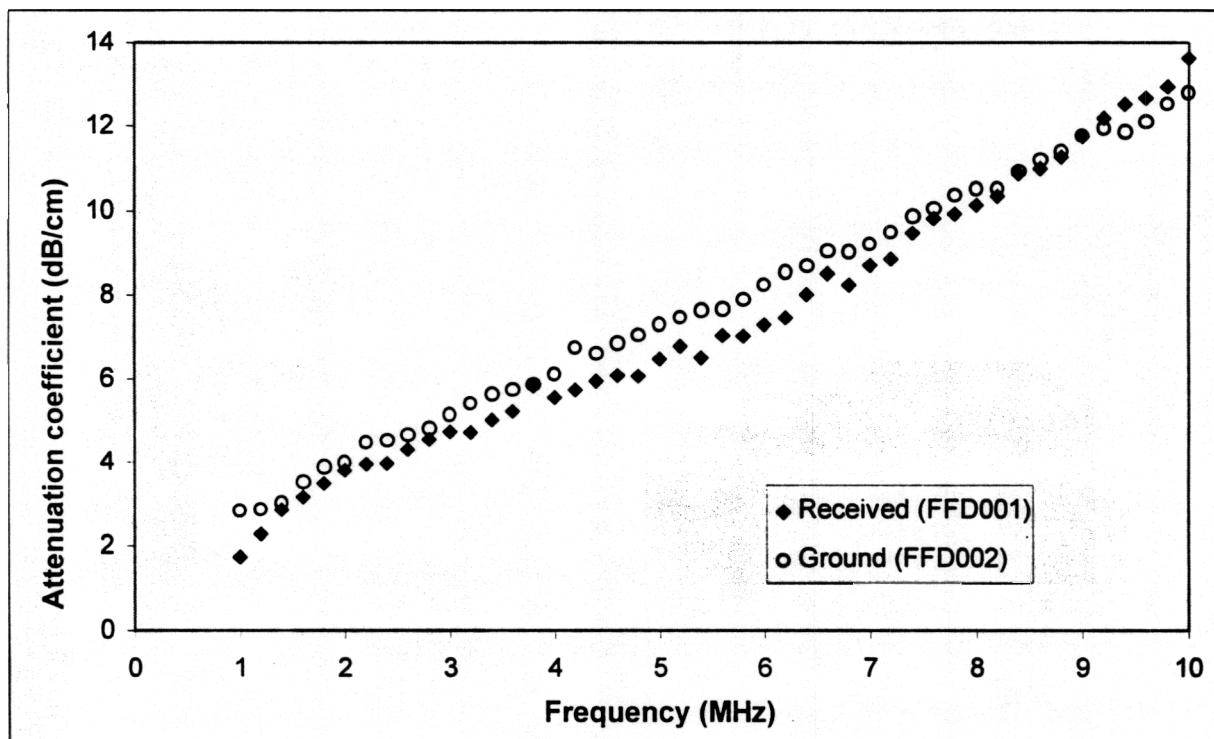


Figure 9.7: Comparison of attenuation coefficient measurements made on the two samples FFD001 and FFD002 whose surface finish differed

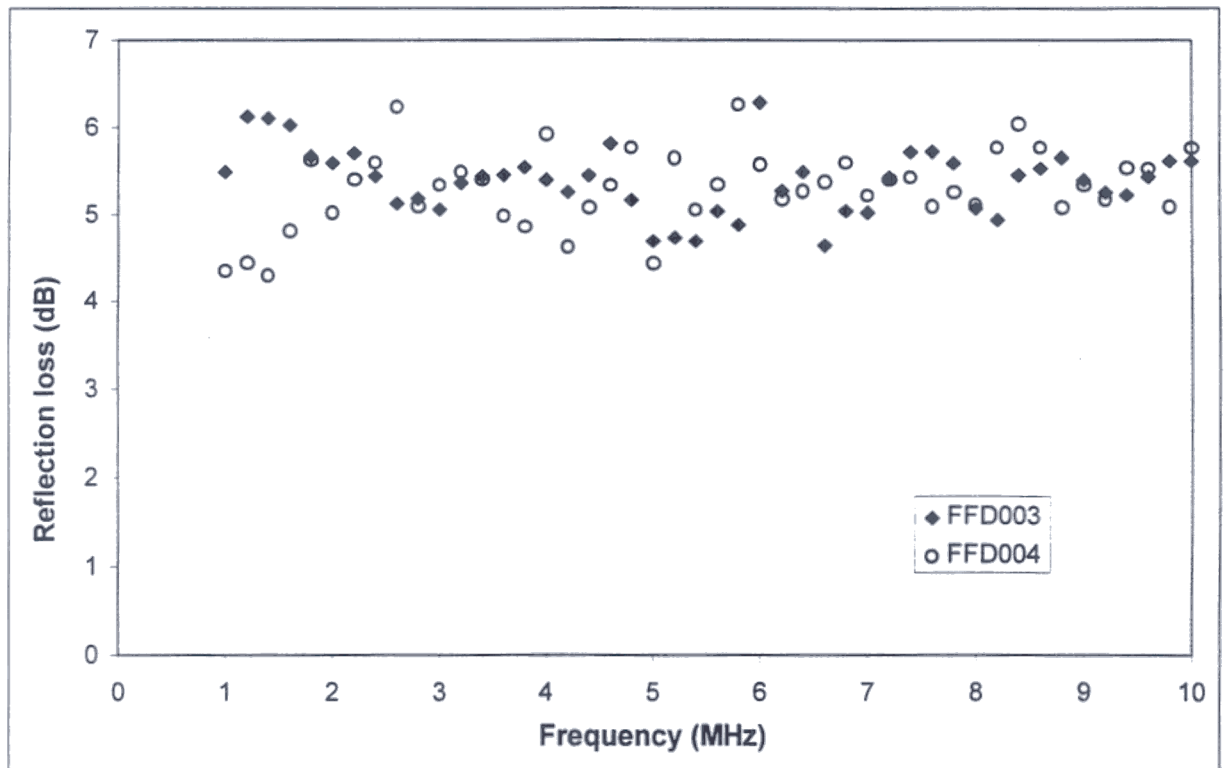


Figure 9.8: Comparison of the measured reflection loss of two carbon-epoxy materials FFD003 and FFD004

The reflection loss (relative to an ideal reflector) of two carbon epoxy samples (FFD003 and FFD004) is shown in Figure 9.8. The random uncertainty on the individual data points is ± 0.5 dB at the 95% confidence level. The results indicate a reflection loss which is broadly independent of frequency and is very similar for the two “as processed” samples.

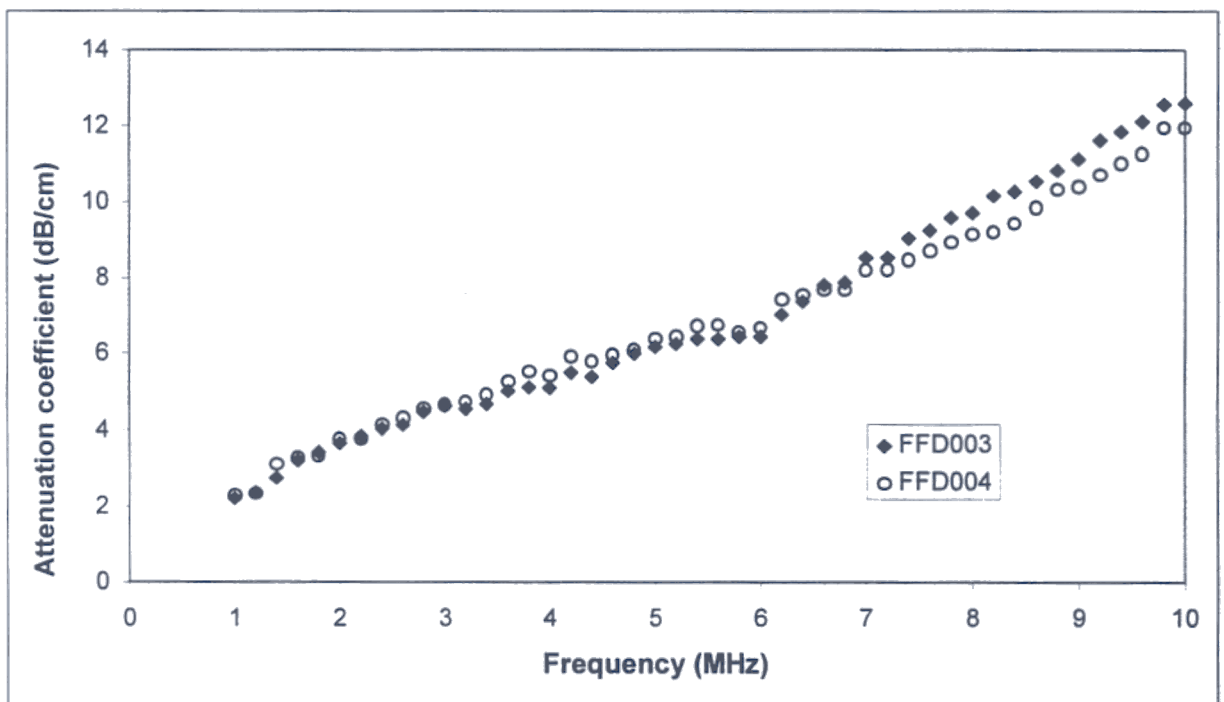


Figure 9.9: Attenuation coefficient data for materials FFD003 and FFD004

9.3.2.2 Sample FFC009

The surface of this nominal 5 mm thick specimen had again been ground. The attenuation coefficient over the frequency range 1 to 10 MHz is given in Figure 9.10.

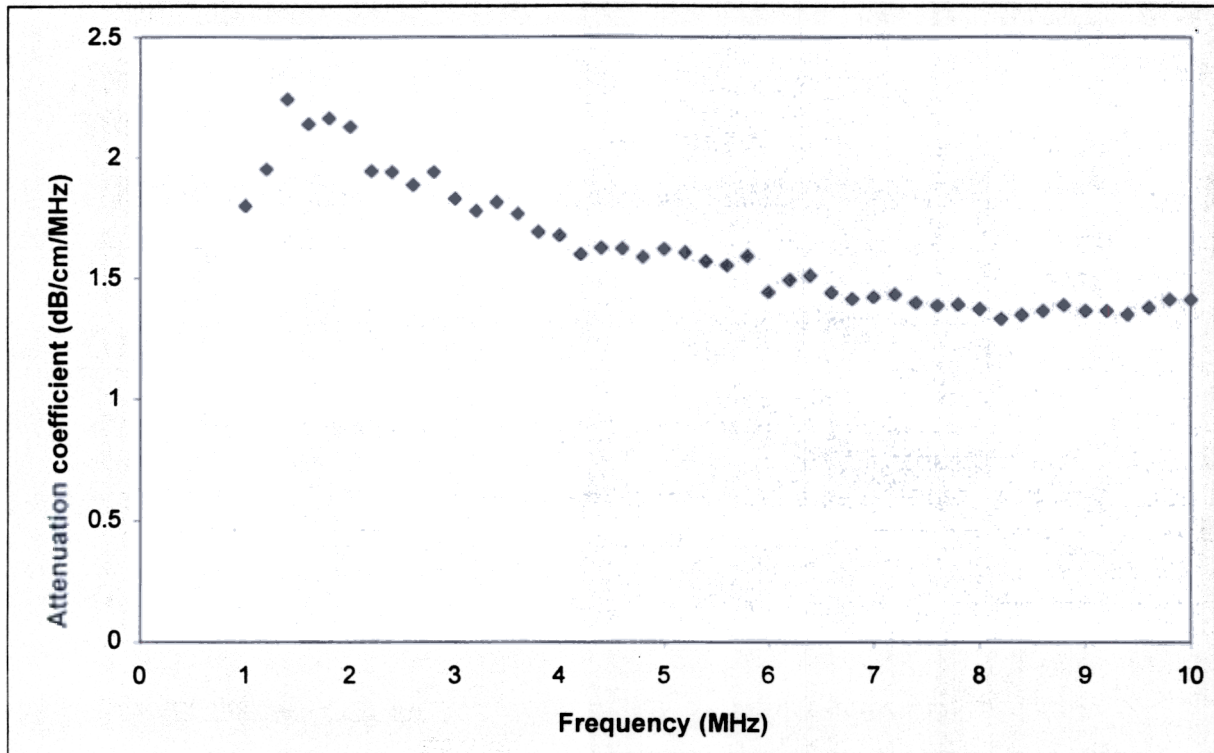


Figure 9.10: Frequency dependent attenuation coefficient of the carbon-epoxy material FFC009

9.3.2.3 Samples FGU002, FGU006

These two specimens were both of nominal thickness 5 mm and again differed in respect to one another through their surface finish: FGU002 was 'as processed' and FGU006 had its surface ground. The attenuation coefficients derived from measurements on the two specimens were very different. This is illustrated in Figure 9.11, where both are plotted in $\text{dB cm}^{-1} \text{MHz}^{-1}$. The magnitude of these differences is surprising and may again be caused by air being secured to the surface of the ground sample.

9.3.3 Glass epoxy material

Two samples of the glass epoxy material were used during the characterisation, of nominal thicknesses 5 mm (FEM002) and 10 mm (FEL004). The high attenuation coefficient of the material restricted measurements of phase velocity and attenuation to frequencies below 5 MHz. The phase velocity, derived from measurements made on the thinner sample, is shown in Figure 9.12 and indicates a dispersion of 60 m s^{-1} over the frequency range.

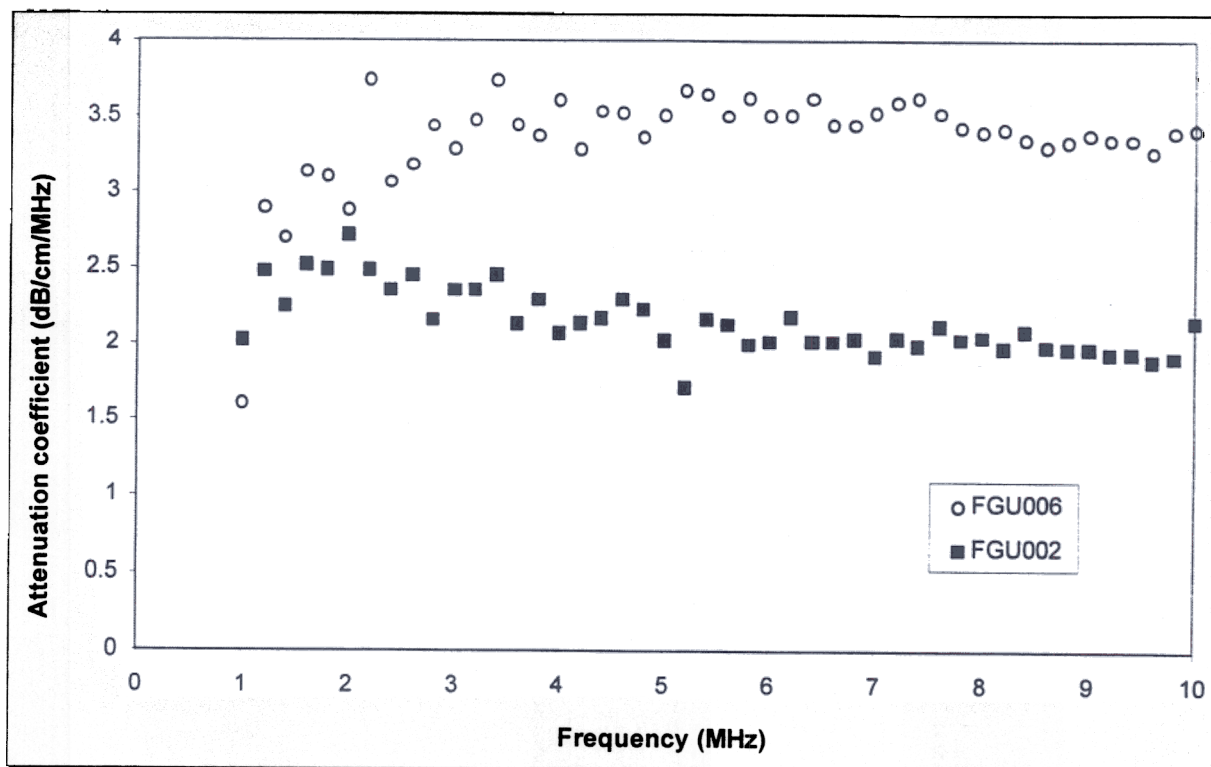


Figure 9.11: Comparison of attenuation coefficient measurements made on carbon-epoxy samples FGU002 and FGU006

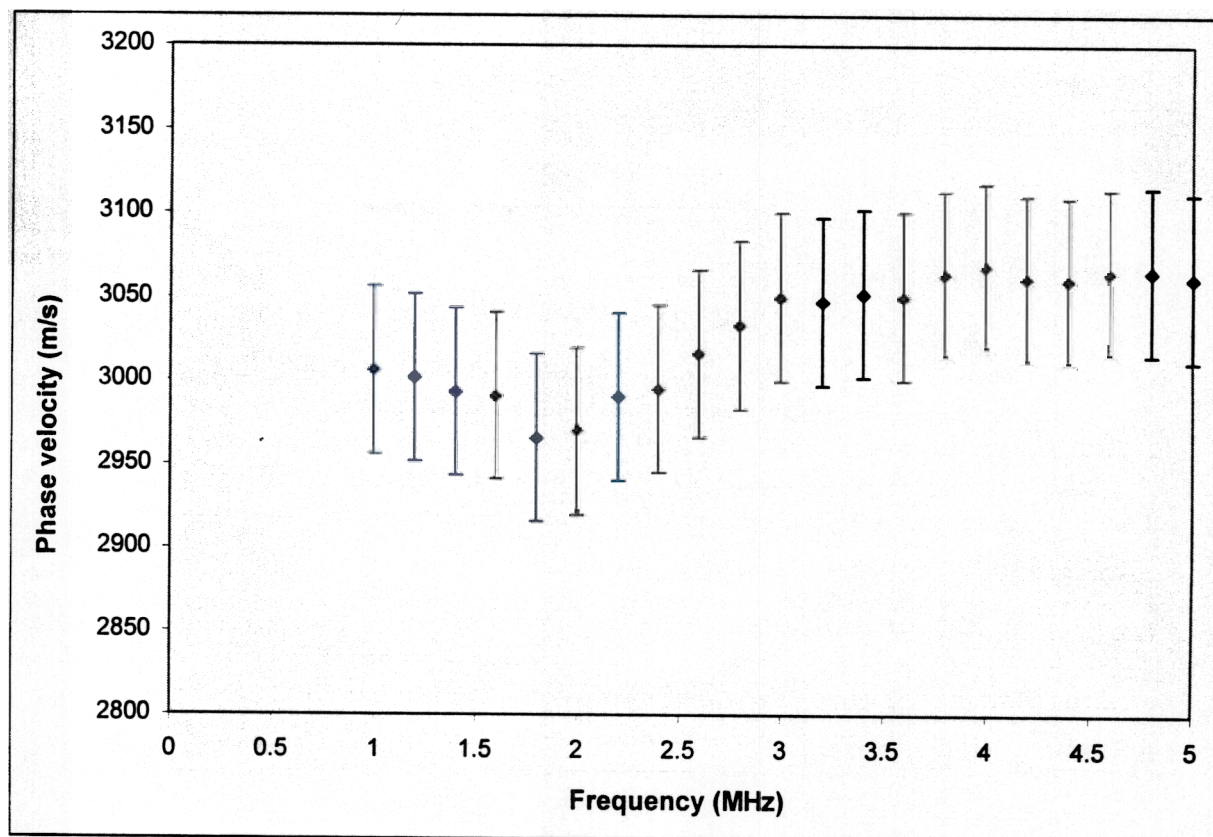


Figure 9.12: Phase velocity measurements made on the glass-epoxy sample FEM002

The reflection coefficient of the water-glass epoxy surface was determined for each of the specimens and used to derive the two interface loss (in dB). The results indicate an interfacial loss which is strongly dependent on frequency and this is shown in Figure 9.13. Agreement between the two samples is good, the random uncertainties associated with the individual frequency points is typically 0.3 - 0.4 dB. The structure in the reflection loss arises from the layered cloth and the resonance at 8.5 MHz indicates a ply thickness of approximately 90 μm .

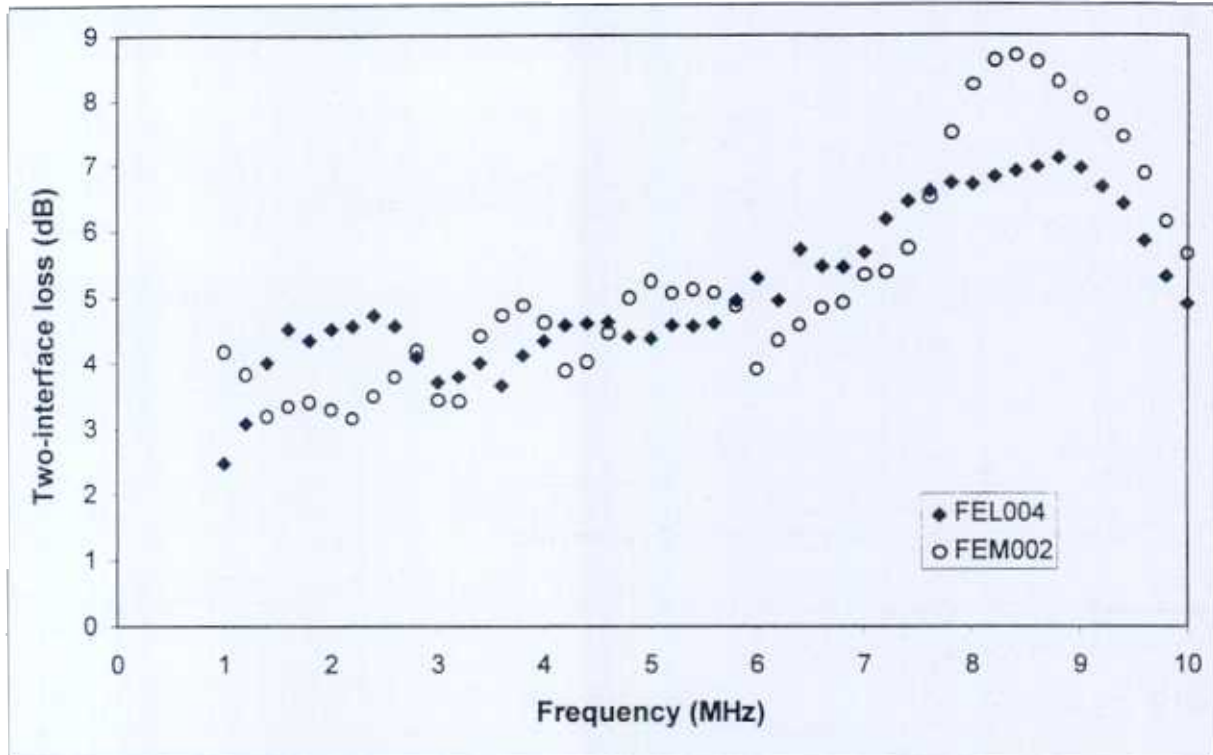


Figure 9.13: The two-interface transmission loss expressed in dB of the two glass epoxy samples FEL004 and FEM002, derived from the reflection coefficients of the glass-epoxy water interfaces

The attenuation coefficient of the glass epoxy is given in Figure 9.14 where the results have been derived in two ways. The first is performed by taking the two specimens individually, assuming that their interfacial losses are identical, and dividing the difference in their transmission losses by the difference in the thicknesses. The second way is to take the individual specimen transmission losses and correct for the interfacial losses given in Figure 9.13. Figure 9.14 illustrates the uncertainties associated with the various methods of calculating the attenuation coefficient. It is appropriate to consider a best fit curve to the three sets of data points, taking an uncertainty which encompasses the spread about this mean best fit.

9.3.4 Cloth weave

Figure 9.15 gives the frequency dependent transmission loss of the 5 mm thick cloth weave specimen IFSX000, where a time window of 5 μs has been used to acquire the transmitted acoustic waveform giving a 0.2 MHz frequency domain resolution. The measurements indicate ply resonances at frequencies of 4.4, 8.6 and 12.6 MHz which were to be avoided in any panel intercomparison performed using this material. The highest frequency resonance

corresponds to the destructive interference condition where the thickness, $d = 3\lambda/4$, indicating a ply thickness of $180\text{ }\mu\text{m}$. The two lower frequency constructive resonances correspond to $d = \lambda/4$ and $d = \lambda/2$. These translate into thicknesses for the ply layer of $170\text{ }\mu\text{m}$ and $180\text{ }\mu\text{m}$ respectively.

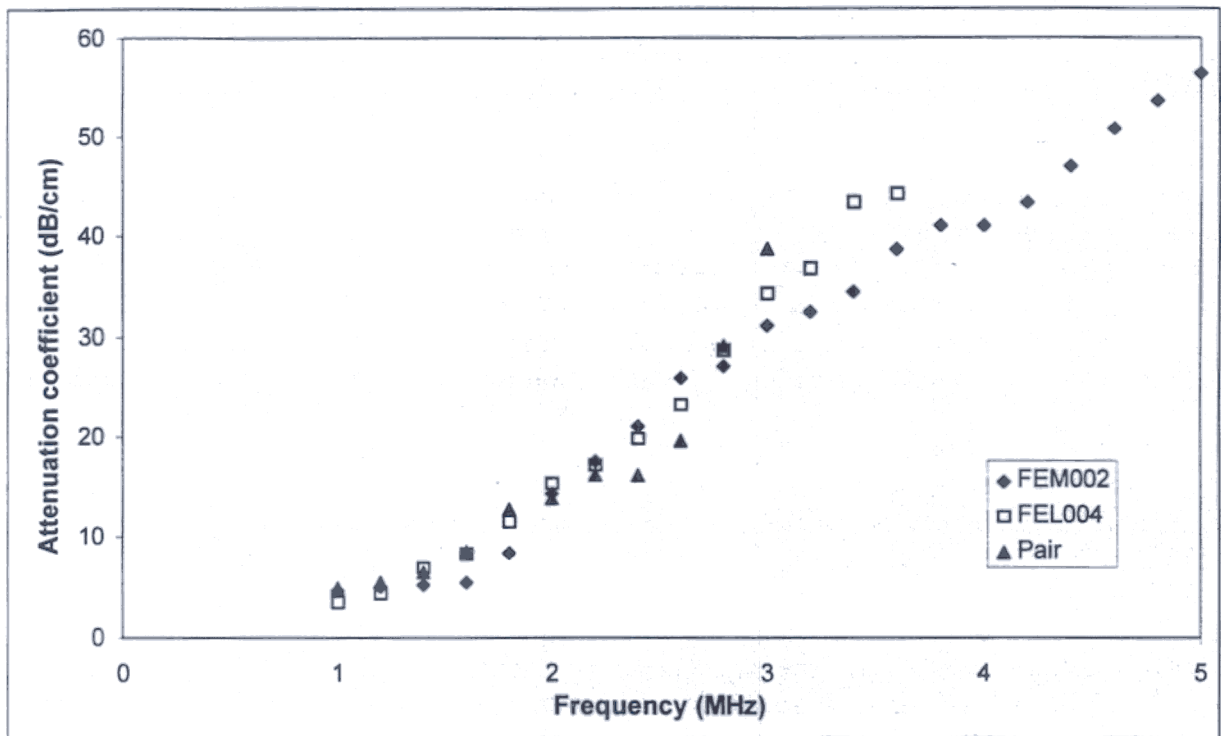


Figure 9.14: Compilation of attenuation coefficient measurements made on the glass epoxy materials derived using the two methods indicated in the text

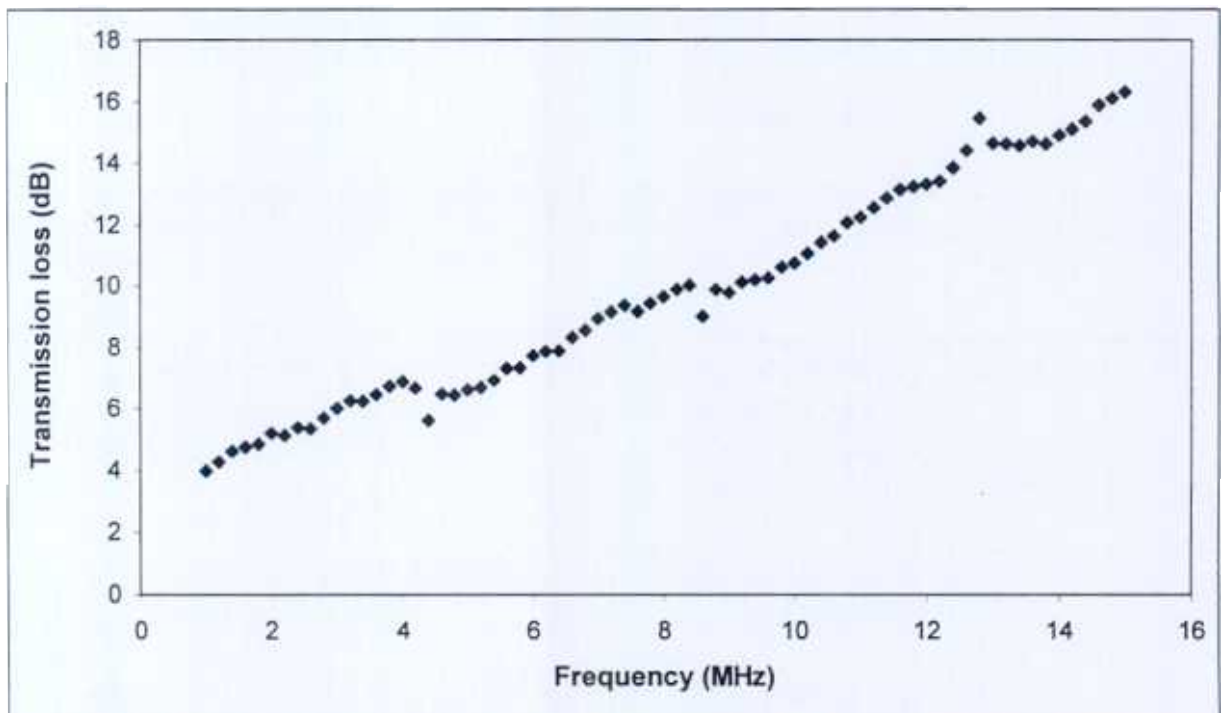


Figure 9.15: Transmission loss of the sample ISFX000 showing the ply resonances

9.3.5 DERA Perspex reference step-wedge panel

The DERA reference step-wedge (identification number NPL-01) consisted of a series of Perspex steps machined to nominal thicknesses of 10 mm, 15 mm, 20 mm and 25 mm. Micrometer measurements made of the step thickness indicated that actual thicknesses were approximately 0.4 mm smaller than the nominal values. Like many other polymers, Perspex absorbs water which inevitably influences its acoustic properties. In an attempt to saturate the material, DERA had kept the step-wedge permanently immersed in water and it was supplied to NPL for measurements in this condition.

The step-wedge was mounted in such a way to enable it to be orientated relative to the front face of the transducer. As the width of the each step was approximately 20 mm, the transducer was positioned close to the step-wedge surface (transducer-Perspex separation < 3 mm) to reduce the effect of any diffraction from neighbouring step-edges. Transmission loss measurements were made on each of the steps, a 4 mm membrane hydrophone being used to acquire the acoustic waveform. During the measurements, the hydrophone was positioned at various distances along the acoustic axis of the transducer with typically, at least three separations being used covering the range 9 cm to 12 cm. This protocol was adopted in an attempt to randomise the effect of diffraction (described in Section 9.3.5.2). At each position, a measurement consisted of four acquisitions of the waveform, both with and without the step-wedge interposed in the acoustic beam. This procedure yielded 16 sets of transmission coefficient data from which the mean transmission losses and random uncertainties for that particular run were calculated. The random uncertainties in the transmission loss measurements were determined by averaging over at least three transducer-hydrophone separations used for the measurements. During the measurements the mean water temperature was 20.5 ± 0.5 °C.

9.3.5.1 Results and analysis of raw data

Figure 9.16 gives the raw transmission loss data (expressed in dB) covering the frequency range 1 to 15 MHz for each of the four step-wedge thicknesses. Figure 9.17 illustrates the transmission loss variation as a function of step thickness at frequencies of 2, 5, 10 and 15 MHz. Each of the data sets exhibits a satisfactory linear dependence (with a regression coefficient $R^2 = 0.995 \pm 0.005$ for all frequencies in the range 1 to 15 MHz) whose slope can be used to derive the attenuation coefficient of the Perspex and whose intercept provides a value for the interfacial loss in dB.

Values of the phase velocity for each frequency have been derived from an average over the four step thicknesses.

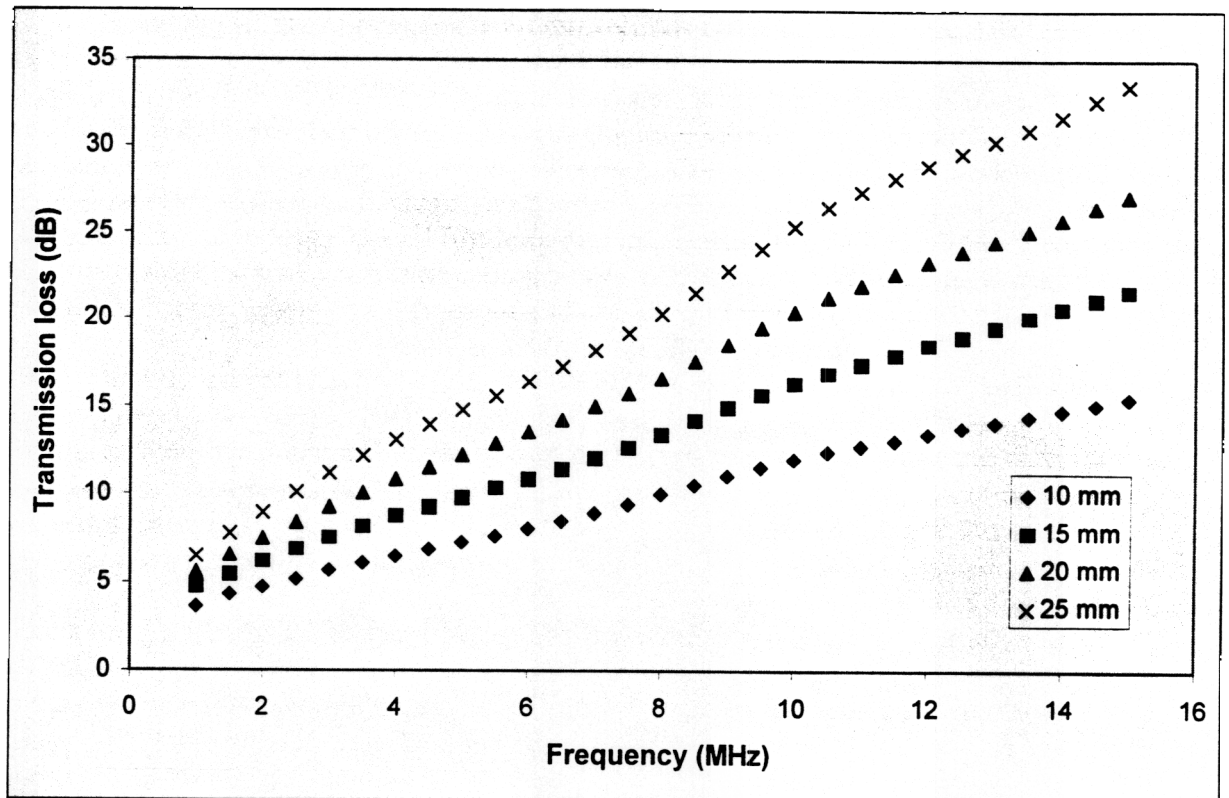


Figure 9.16: Transmission loss measurements made on the four nominal step thicknesses of the DERA reference Perspex step-wedge

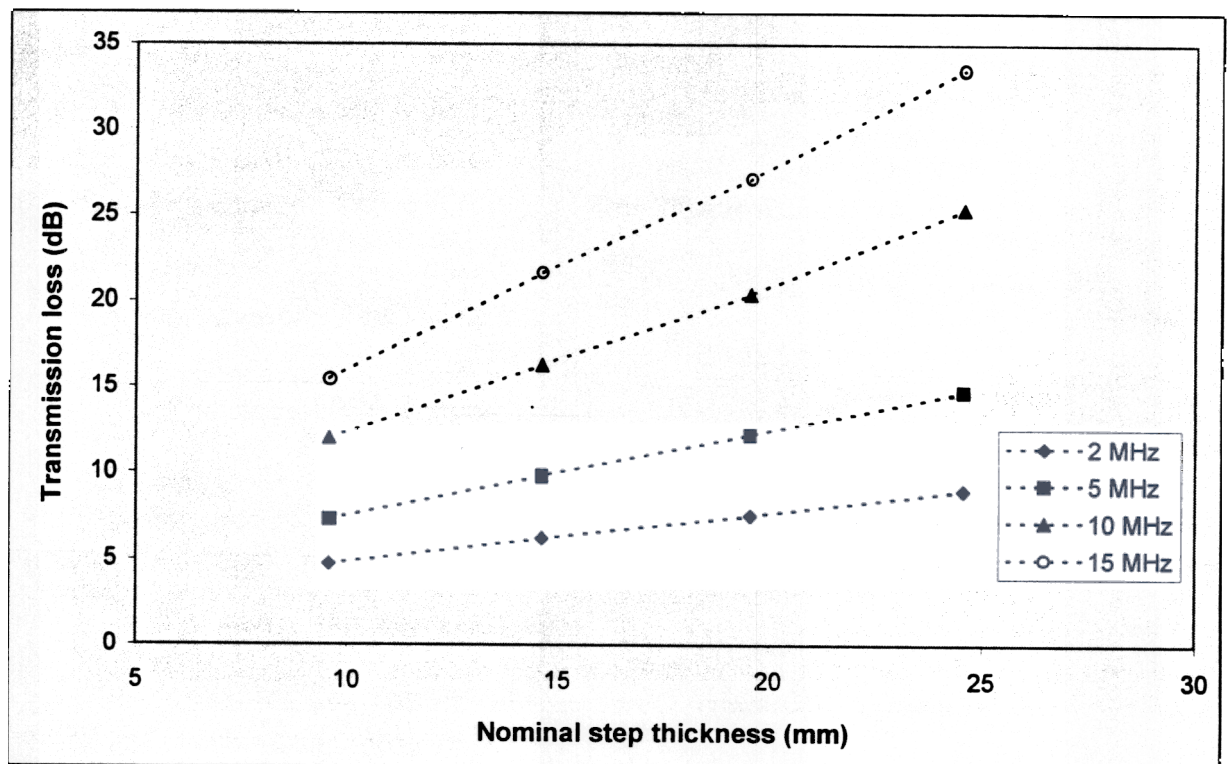


Figure 9.17: Linearity of measured transmission loss with thickness for the four steps of the DERA reference Perspex step-wedge at a number of frequencies

9.3.5.2 Correction of measurements for diffraction

The effect of diffraction on the measured Perspex transmission loss and therefore the derived attenuation coefficient was evaluated according to Zeqiri⁹. The effect of inserting a sample of thickness Δz into the acoustic beam is to shift the receiver to a new 'effective' position given by:

$$z_{eff} = z_0 + \Delta z \left(\frac{c_2}{c_1} - 1 \right)$$

where z_0 is the separation between the transducer and hydrophone and c_2 and c_1 are the propagation speeds for ultrasound in the material under test and in water respectively. Evaluation of the effect of diffraction is undertaken by computing the average pressure over the face of the receiver positioned on the axis of the transmitting transducer at the two positions z_0 and z_{eff} . To do this an analytical model given by Williams¹⁰ was used.

The results of calculations carried out for the Perspex step-wedge is given in Figure 9.18 covering the frequency range 1 to 15 MHz. Calculations for the 10 mm, 15 mm and 25 mm step-wedge have been included only, with the 4 mm diameter hydrophone positioned 90 mm away from the transducer face. Note that in Figure 9.18, a negative diffraction loss results in an increased measured transmission loss for the specimen. Note also the significant diffraction loss below 3 MHz: this has a substantial effect on the transmission loss due to the reduced intrinsic absorption in Perspex at low MHz frequencies. In contrast, the effect of diffraction on propagation speed is small ($< \pm 3 \text{ m s}^{-1}$) at all frequencies.

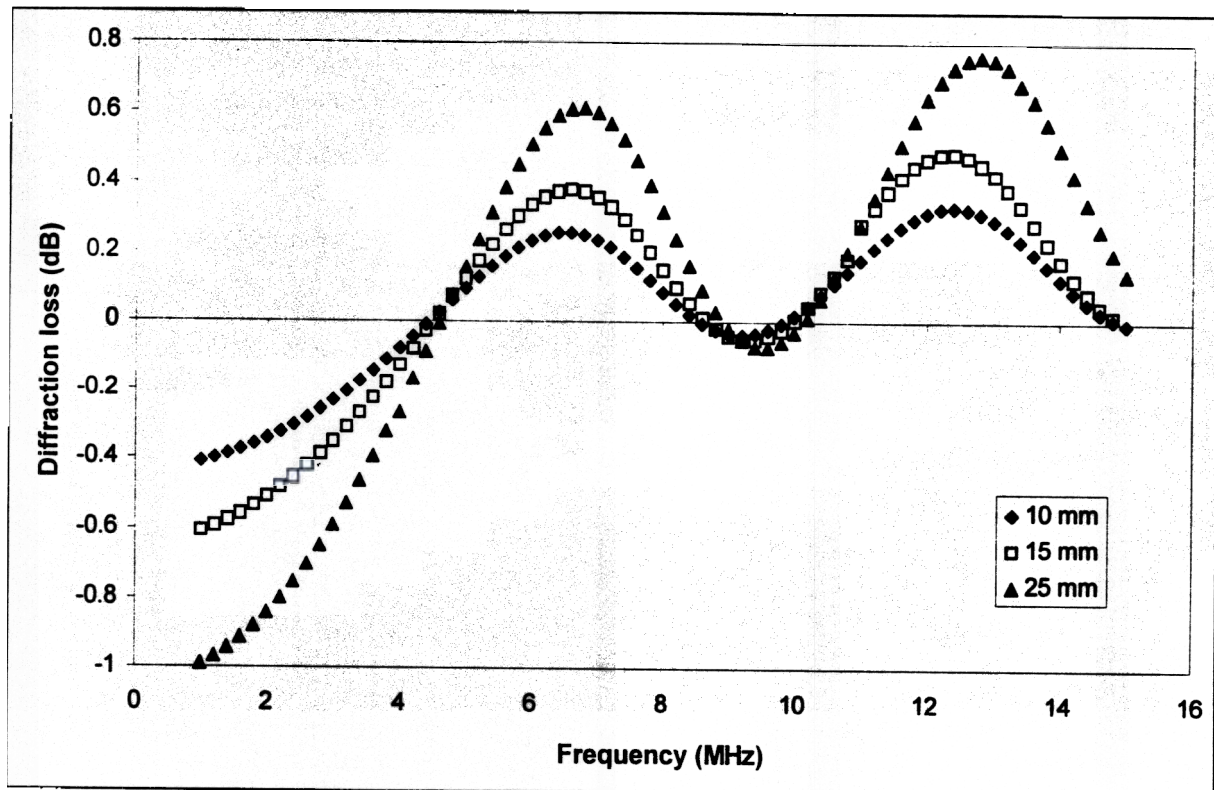


Figure 9.18: Diffraction loss values for measurements made on Perspex using a typical through-transmission substitution set-up for thicknesses of 10, 15 and 25 mm. Calculations have been carried using the model of Williams¹⁰.

9.3.5.3 Diffraction corrected data

Calculations of the type shown in Figure 9.18 have been used to correct the raw transmission loss data shown in Figure 9.16. This corrected data was then processed through linear regressions undertaken on the four data values at each of the frequencies used which yielded the attenuation coefficient (expressed in $\text{dB cm}^{-1} \text{MHz}^{-1}$) dependence shown in Figure 9.19. For comparison purposes, the attenuation coefficient has also been presented in Figure 9.19, derived from raw data without correcting for diffraction.

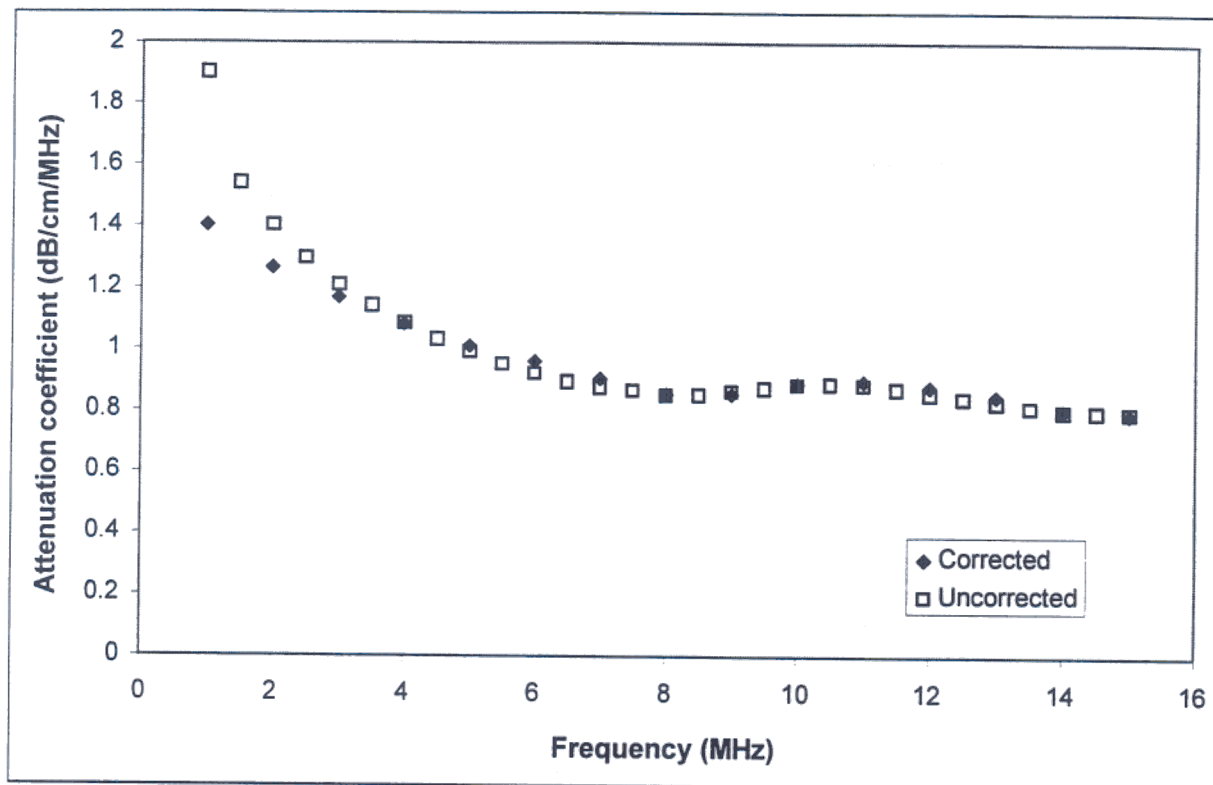


Figure 9.19: Attenuation coefficient values for Perspex of the DERA step-wedge with and without correction for diffraction

Additionally, for both data sets, the attenuation coefficient has been corrected due to attenuation in the water path displaced by the step-wedge thickness in the acoustic beam. The resultant correction is small, even at 10 MHz, for the 25 mm Perspex step, it corresponds to only 0.55 dB in comparison to the transmission loss of 25.3 dB. Table 9.3 gives the attenuation coefficient of the Perspex at several frequencies along with the relevant phase velocities.

Figure 9.20 gives the frequency dependence of the interfacial loss in dB, which was derived from the intercept of the linear regression of the diffraction-corrected data. The results indicate an interfacial loss significantly greater than that expected simply from a consideration of the acoustic impedance mismatch of the water-Perspex surface. Appendix F gives a compilation of literature values of the acoustic properties of Perspex, from these, taking a density value of 1.19 g cm^{-3} and a propagation speed of 2720 m s^{-1} , the two-face interfacial loss may be derived as 1.28 dB. This is clearly considerably smaller than the interfacial loss demonstrated in Figure 9.20, which increases from approximately 2 dB at 1 MHz to a level of 4 dB at 15 MHz and exhibits significant structure over the frequency range 8 to 12 MHz.

Table 9.3: Compilation of attenuation coefficient measurements made on the DERA reference step-wedge, corrected for the effect of diffraction

Frequency (MHz)	Attenuation coefficient (dB cm ⁻¹ MHz ⁻¹)	Phase velocity (m s ⁻¹)
2	1.27	2740
5	1.02	2749
10	0.91	2754
12	0.93	2756
15	0.83	2757

It should also be noted that the structure seen in Figure 9.20, with the maxima seen at frequencies of 9 MHz and 14 MHz, bears some similarity to the structure seen in the diffraction calculations shown in Figure 9.18. This may be taken to imply that diffraction corrections have been underestimated, and this should be taken into account in the uncertainty analysis given in Section 9.3.4.4.

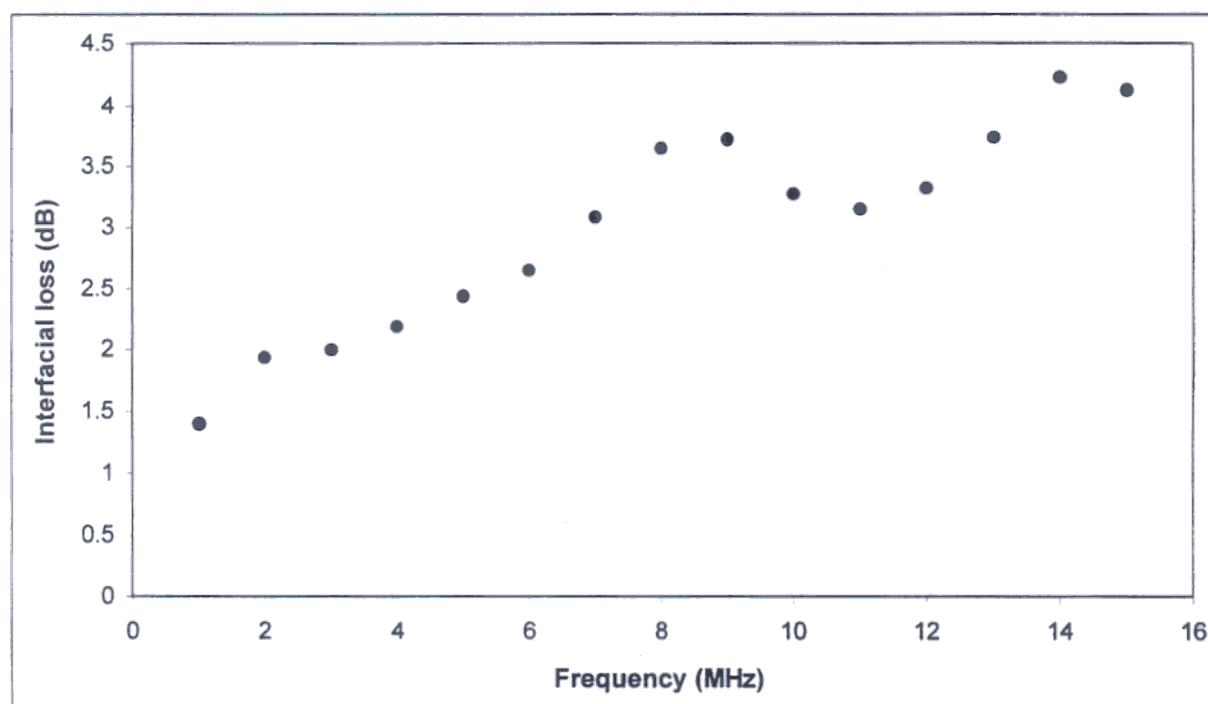


Figure 9.20: Variation of the interfacial loss of the DERA reference Perspex step-wedge derived from a linear regression of the individual step-wedge transmission losses

With the step-wedge being held for a limited time, no further studies were possible to investigate the origin of this seemingly enhanced interfacial loss. A single water-Perspex interfacial loss of 2 dB implies a reflection coefficient of 60% (compared to a 'normal' value of 37%) and a test of the reflection (front-wall echo) might prove instructive, although it is

doubtful whether this degree of enhancement in the front wall echo will actually be seen. From measurements made on another sample of Perspex (see Appendix F) at NPL, there is evidence that a two-interface loss of 1.28 dB can be used reasonably accurately to correct transmission loss data. These measurements, however, were made with the specimens submitted to relatively short immersion times (less than 30 minutes), and this would seem to point tentatively to a prolonged immersion altering the nature of the interfacial layer. It could introduce a relaxation mechanism associated with the way in which water is bound within the polymer matrix which increases the interfacial loss through a 'bulk' type mechanism.

Despite these uncertainties regarding the nature of the interfacial layer, it is instructive to consider what other mechanisms could lead to the observed systematic effect. One possibility could lie in the non-parallelism of the two step-wedge interfaces. Although the effect on pulse-echo FWE-BWE attenuation would be much greater, there may still be an effect on transmission measurements and the effect would increase with frequency through the directional response of the hydrophone. An improved specification for manufacture of the step-wedge would serve to reduce or eliminate this problem.

Another possibility lies in nonlinear propagation. Even in situations where low acoustic pressures are used (20-30 kPa), due to the broadband nature of the acoustic waveform, propagation through the water may not actually be linear. In particular, nonlinear loss from the rear of the sample to the hydrophone may arise which will be dependent on the transmission loss of the step-wedge. In order to minimise the effect, one would need the sample to be close to the hydrophone (or ideally, transducer, sample and hydrophone all close to one another), however, this could not be done due to concerns over diffraction at the step-edges and limitations in the mounting hardware. If nonlinear effects were important, the transmission loss of the specimen might be expected to depend on the position of the hydrophone in the field although no clear systematic trend with distance was observed in the results obtained at various distances.

9.3.5.4 Assessment of overall measurement uncertainty

Characterisation of the Perspex step-wedge NPL-01 was carried out to underpin the DERA absolute attenuation study. For this reason, it is clearly important to assess the accuracy of the attenuation measurements made using the through-transmission substitution technique. The effect of diffraction has been dealt with in Section 9.3.5.2 for the through-transmission substitution set-up, the results being presented in Figure 9.18 for three of the step-wedge thicknesses. In view of the relatively small size of the effect, no direct correction was applied to the data, but a Type B (systematic) measurement uncertainty was taken equal in size to the contribution. It can be seen from Figure 9.19 that the influence of diffraction on the measured transmission may effectively be ignored above 3 MHz.

Table 9.4 gives a summary of the expanded uncertainty values, where the components have been calculated and combined according to Edition 8 of NIS 3003¹¹. Type B components considered include: linearity of the measurement system, temperature, alignment, water attenuation, time-base accuracy, non-planarity of interfaces and the effect of nonlinear propagation.

Table 9.4: Expanded measurement uncertainties in absolute attenuation measurements for the DERA Perspex step-wedge (NPL-01) at five frequencies. The measurement uncertainties have been calculated according to NIS 3003 Edition 8¹¹.

Frequency (MHz)	Expanded measurement uncertainty (dB cm ⁻¹ MHz ⁻¹)
2	± 0.19
5	± 0.065
10	± 0.055
12	± 0.06
15	± 0.05

9.4 SUMMARY

The Section has presented the results of attenuation, phase velocity and reflection loss measurements made on a range of materials relevant to the project. In support of the DERA programme on absolute measurement of attenuation, a reference Perspex step-wedge was characterised using a through-transmission substitution technique over the frequency range 1 to 15 MHz.

10 STUDY OF THE EFFECT OF NONLINEAR DISTORTION ON ABSOLUTE MEASUREMENT OF ATTENUATION

This Section presents the results of an investigation carried out to establish and model the influence of nonlinear distortion on measured C-scan attenuation. The specific C-scan configuration studied is the front wall echo (FWE) - back wall echo (BWE) pulse-echo method. Here, it is the enhanced fundamental loss arising through nonlinear propagation in both directions through the intervening water path which gives rise to a major source of measurement uncertainty in the absolute attenuation of the material under test.

10.1 GENERALIZED MODEL OF THE EFFECT OF NONLINEAR DISTORTION

Figure 10.1 represents a schematic of the measurement set-up, illustrating the specimen of thickness Δz positioned on the acoustic axis, at a distance of z_1 with the transducer itself positioned at z_0 .

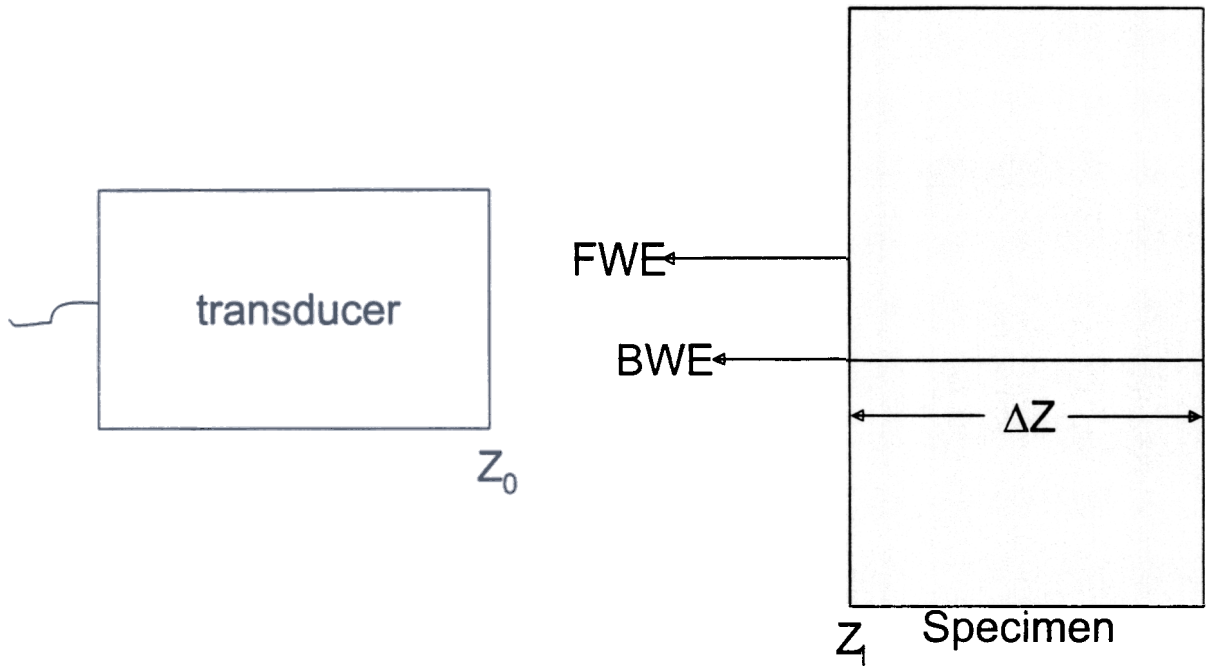


Figure 10.1: Schematic representation of the pulse-echo, FWE-BWE configuration showing the transducer positioned at z_0 and the specimen under test at z_1

If p_0 is the pressure at the face of the transducer, then we can express the pressure at the face of the specimen as $p_0 \cdot L_1(z_0 \rightarrow z_1)$ where $L_1(z_0 \rightarrow z_1)$ represents the nonlinear loss in the fundamental frequency component incurred in travelling from position z_0 to z_1 . If we take the linear extreme, then $L_1(z_0 \rightarrow z_1) = 1$, but in the more general case $L_1(z_0 \rightarrow z_1) < 1$. Using this type of convention, the following expressions may be derived for the front wall echo (FWE) and back wall echo (BWE) signals received from the specimen, where we are again considering only the narrowband measurement condition and are interested in the fundamental component of the signal:

$$\text{FWE signal} \quad p_0 \cdot L_1(z_0 \rightarrow z_1) \cdot r \cdot L_2(z_1 \rightarrow z_0)$$

$$\text{BWE signal} \quad p_0 \cdot L_1(z_0 \rightarrow z_1) \cdot t_1 \cdot \exp(-2 \alpha \Delta z) \cdot r \cdot t_2 \cdot L_3(z_1 \rightarrow z_0)$$

where the nomenclature given above regarding the loss terms L_2 and L_3 has been observed, and these relate to the loss in the fundamental signal level produced through the acoustic wave travelling from the front face of the specimen (the face directly in front of the transducer) back to the face of the transducer. The terms t_1 and t_2 represent the transmission coefficients of the two specimen-water surfaces and r is the reflection coefficient of the water-specimen interface. The parameter α is the intrinsic attenuation coefficient in the material. Further assumptions of the model are that there is no nonlinear loss in the material and any linear loss incurred within the water medium may be ignored.

The derived FWE-BWE attenuation is related to the ratio of these two signal levels (designated by the term RR within this report) which, following a suitable restructuring of the equation, may be represented as:

$$\frac{RR}{RR_0} = \frac{L_3(z_1 \rightarrow z_0)}{L_2(z_1 \rightarrow z_0)}$$

Here, RR_0 is the linear FWE-BWE reflection ratio. Generally, $RR > RR_0$, as the reduced acoustic amplitude of the BWE emerging from the material will ensure a smaller nonlinear loss than the FWE. In the extreme case of high attenuation of the specimen the ratio $RR/RR_0 \rightarrow 1 / L_2(z_1 \rightarrow z_0)$ as $L_3(z_1 \rightarrow z_0) \rightarrow 1$. Taken overall, it can be seen that the effect of nonlinear loss of the fundamental will be to underestimate the derived attenuation.

This treatment is very generalised, but may be used at a qualitative level to derive an understanding of the way nonlinear loss will affect measured attenuation in any C-scan configuration. It is anticipated that the extent of the actual underestimate will depend on a number of parameters describing the experimental conditions. Principal amongst these is the acoustic pressure generated at the source (transducer) but also likely to be important are the separation between the transducer and test specimen as well as the transmission properties of the material.

10.2 A SPECIFIC MODEL OF THE INFLUENCE OF NONLINEAR DISTORTION

The extent to which nonlinear or finite amplitude distortion has occurred in any experimental situation is commonly described by a parameter σ , known as the shock parameter. This has been mentioned previously in Section 5 in relation to the assessment of nonlinear distortion, and further information on σ may be found in the two indicated references^{12,13}. Here a brief overview of basic theory will be presented in order to describe the developed model.

For plane-progressive waves propagating in a lossless medium, $\sigma = \beta \varepsilon k z$, where k is the acoustic wavenumber and z is the propagation distance. The quantity β characterises the degree of nonlinearity in the propagation medium, and for water has a value of 3.6. The parameter ε is the acoustic Mach number and is related to the pressure amplitude of the acoustic disturbance at the source (p_0) by the expression $\varepsilon = p_0 / \rho c^2$, where ρ and c are the density and speed of sound in the medium respectively.

In the case of the 5 MHz transducer on which the FWE-BWE measurements (presented in Section 10. 3) were made, we are specifically interested in predicting the values of σ within the transducer near-field and beyond the last-axial maximum of the plane-piston source. Muir and Carstensen^{12,13} have modelled such emitters as weak, self-focused sources whose

effective radius of curvature (R_C) may be taken as twice the position of the last-axial maximum (i.e. equal to $2Y_{0+}$).

For such a source, the corresponding value of σ is given by

$$\sigma = -\sigma_0 \ln(z/R_C) \quad (10.1)$$

where $\sigma_0 = \beta p_0 k R_C / (\rho c^2)$, the equation being valid for a spherically converging source and σ represents the relative increase in nonlinear distortion above that of an equivalent, unfocused, source placed at a distance R_C . The calculation of σ for the two specific parts of the acoustic field of relevance is summarised in Table 10.1.

Table 10.1: Table defining the calculations of the shock parameter, σ

Regime	Details of model used
$z < Y_{0+}$	Within the near-field of the acoustic source, assume self-focusing of source of radius of curvature $2Y_{0+}$ and use equation 10.1 to calculate the value of σ at any position.
$z > Y_{0+}$	As above, for distances $z < Y_{0+}$ assuming self-focusing of source of radius of curvature $2Y_{0+}$. Beyond Y_{0+} , assume pressure distribution of the fundamental component along the acoustic axis is that of a piston source, integrating over the pressure profile to calculate the increase in σ over its value at $z = Y_{0+}$.

To keep the model simple, for the BW and FW echoes, the change in the shock parameter incurred during propagation from the front surface of the specimen back to the transducer face was calculated assuming plane-wave propagation.

The fundamental loss $L(\sigma)$ associated with a particular shock parameter value of σ , was calculated using the 'bridging' function derived by Blackstock¹⁴ which is appropriate for both plane and spherical waves. Important benchmarks of note for the fundamental loss occur at σ values of 1 and 3, where losses in fundamental signal amplitude are -1 dB and -6 dB respectively. The $\sigma = 1$ condition represents the point when the acoustic waveform is distorted to such an extent such that an infinitesimal shock first forms.

In order to calculate the effect of nonlinear distortion on FWE-BWE attenuation a MATHCAD program was written which enabled the C-scan attenuation measurement configuration to be simulated. Input parameters to the program included the acoustic properties of the material and the acoustic drive conditions, given by the input pressure at the face of the transducer. Calculations derived using the model are shown in Figure 10.2, for FWE-BWE attenuation made on Perspex of approximate thickness 15 mm. Here, three specific drive conditions are used with the RR value being calculated at a range of transducer-specimen separations. Calculations were performed for a 5 MHz transducer equivalent to the one used for the measurements described in Section 10.3. These conditions correspond to pressure amplitudes of 0.2 MPa, 0.6 MPa and 0.9 MPa which translate into σ

values at the position of Y_{0+} of 0.5, 1.5 and 2.3. Note the relatively rapid increase in the ratio RR which occurs with the sample position close to Y_{0+} for the two higher drive levels.

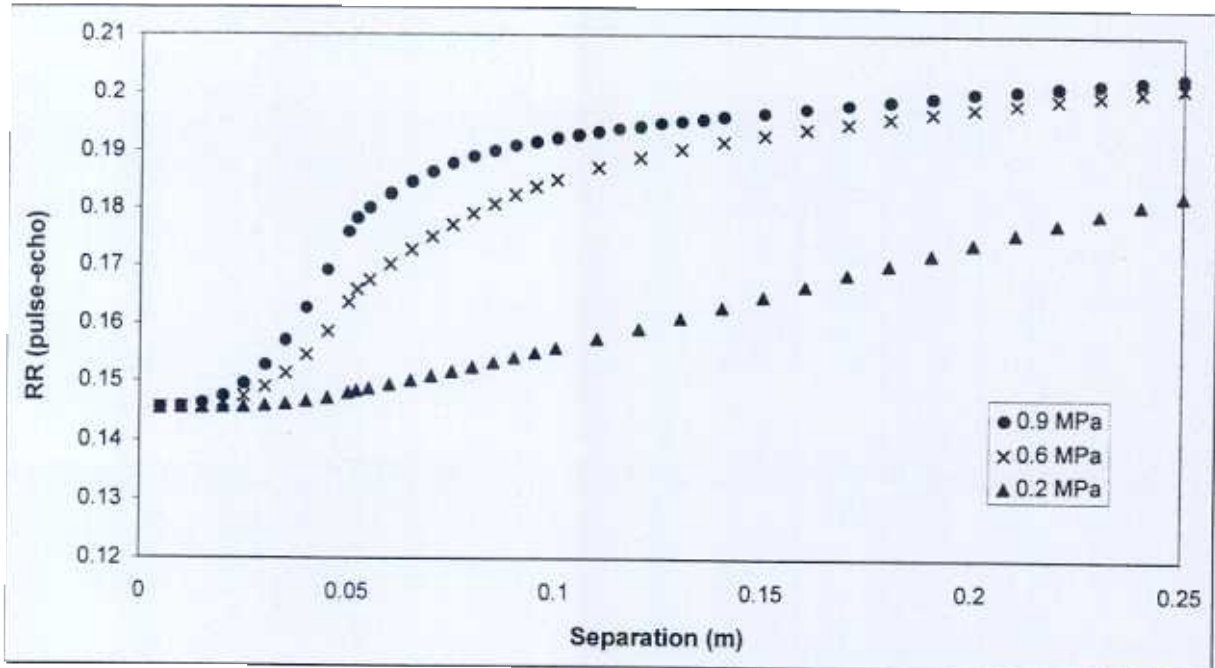


Figure 10.2: Variation of the measured FWE-BWE reflection ratio (RR) with separation between transducer and specimen for three values of the source pressure amplitude. The calculations were performed for a 5 MHz unfocused transducer piston transducer whose Y_{0+} value was 52 mm, using the MATHCAD programme described in the text

Measurements of FWE-BWE attenuation were corrected for diffraction using the analytical model given by Williams¹⁰ to calculate the pressure integrated over the surface of a receiver placed at various positions on the acoustic axis of the source. This particular model is valid for $z > 0.2 a^2/\lambda$ (where a^2/λ is taken to be equal to Y_{0+}); for distances less than this, diffraction corrections were derived from the work of Brendel and Ludwig¹⁵. Figure 10.3 gives the magnitude of the diffraction correction for the 5 MHz transducer of interest as a function of the two-way propagation distance. For the BWE the effective propagation distance used to calculate the magnitude of the diffraction correction was taken as $2(z + c_m \Delta z)$, where c_m is the propagation speed in the material and Δz is the thickness of specimen.

10.3 MEASUREMENT PROGRAMME

10.3.1 Materials, transducer and protocol

FWE-BWE pulse-echo measurements were made using the Meccasonics drive unit in conjunction with an unfocused 5 MHz transducer (F11941135). Measurements were made on two different specimens, both of which had been machined to ensure parallelism of the front and rear surfaces. The first of these consisted of a 20 mm thick right-circular cylinder of cross-linked polystyrene, a material whose acoustic properties were well known⁹. The second sample, of thickness 14.6 mm, was made of Perspex. The relevant acoustic properties of the materials are illustrated in Table 10.2. The use of two materials of quite different acoustic properties was considered to be good test of the developed model.

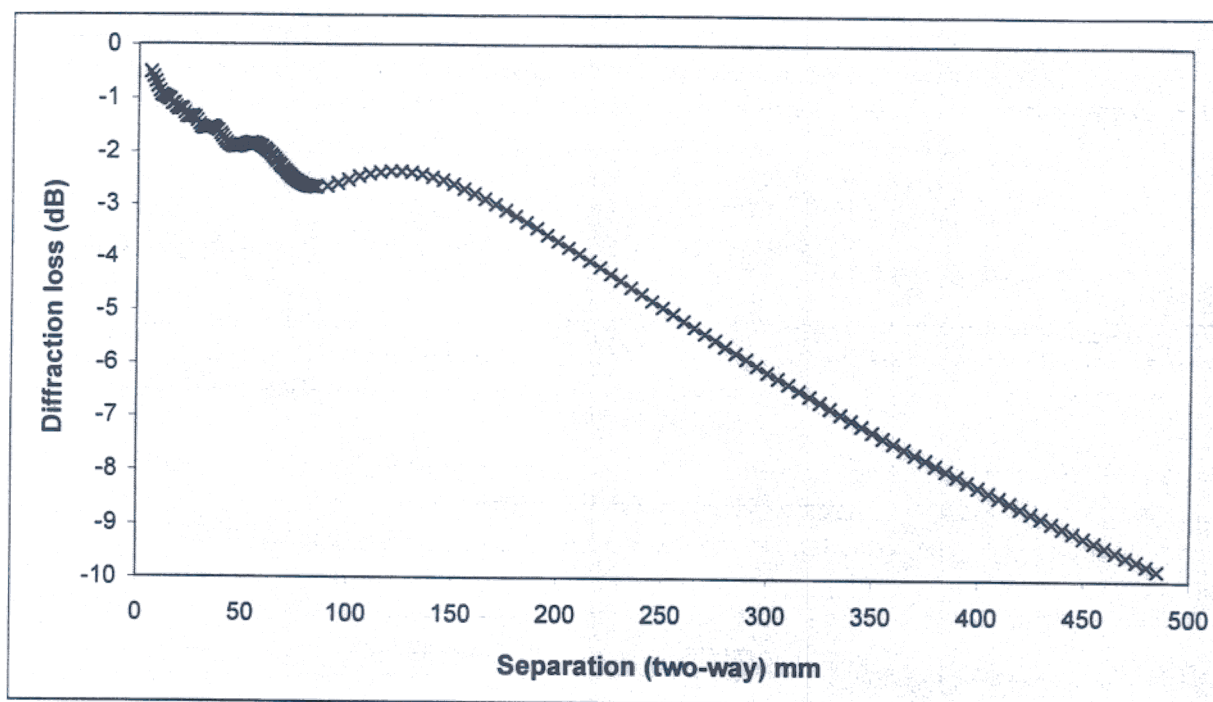


Figure 10.3: Diffraction loss for the 5 MHz unfocused transducer used during this nonlinear study

Table 10.2: Compilation of the acoustic properties for the two materials used during the 5 MHz nonlinear loss study

Material details	Attenuation	Propagation speed
Cross-linked polystyrene	Intrinsic absorption coefficient: $0.3344 \text{ dB cm}^{-1} \text{ MHz}^{-1}$ Interfacial loss (two interfaces): 0.545 dB	2340 m s^{-1}
Perspex	Intrinsic absorption coefficient: $1.06 \text{ dB cm}^{-1} \text{ MHz}^{-1}$ (5 MHz) Interfacial loss (two interfaces): 1.28 dB	2720 m s^{-1}

FWE-BWE measurements of attenuation were made using various transducer-specimen separations and at each of these the relative orientation of the specimen (tilt and rotation) was adjusted to maximise the magnitude of the front-wall echo. During this process, in all cases, it was found in maximising the FWE, the back-wall echo was simultaneously maximised, indicating that the effect of any non-parallelism of the two interfaces was indeed small. At each separation, the ratio RR was derived using analysis of the following:

voltage parameters derived from the FWE and BWE waveforms, these being the peak-positive voltage (v_+), peak-negative voltage (v_-) and the *rms* voltage (v_{rms});

the 5 MHz magnitude component derived from FFT's of the two waveforms (v_{fft}).

10.3.2 Characterisation of the nonlinear acoustic field

The acoustic waveform generated by the 5 MHz transducer used in conjunction with the Meccasonics drive unit (at the low frequency setting) was acquired at three axial positions both to assess the degree of nonlinear distortion and to provide input data for the model described in Section 10.2. Figure 10.4 shows the acoustic waveform acquired at a distance of 59 mm, which corresponds to the distance at which the maximum of the peak-positive pressure occurs, derived using a hydrophone. The characteristics of the acoustic waveform, the strong asymmetry and the shocked wavefront, are typical of the waveforms demonstrated in Section 4 of this report.

The figure illustrates a peak-to-peak acoustic pressure of 4.2 MPa. Measurements made close to the source (at a separation of 5 mm), gave a peak-to-peak pressure amplitude of 1.9 MPa. When measured using a low-pass filtered hydrophone output, designed to isolate the fundamental component, the modified last axial maximum of the signal occurs at 52 mm and using this, a value of 3.9 mm was derived for the effective radius of the piston source. This was used in the nonlinear model to predict the properties of the unfocused transducer field.

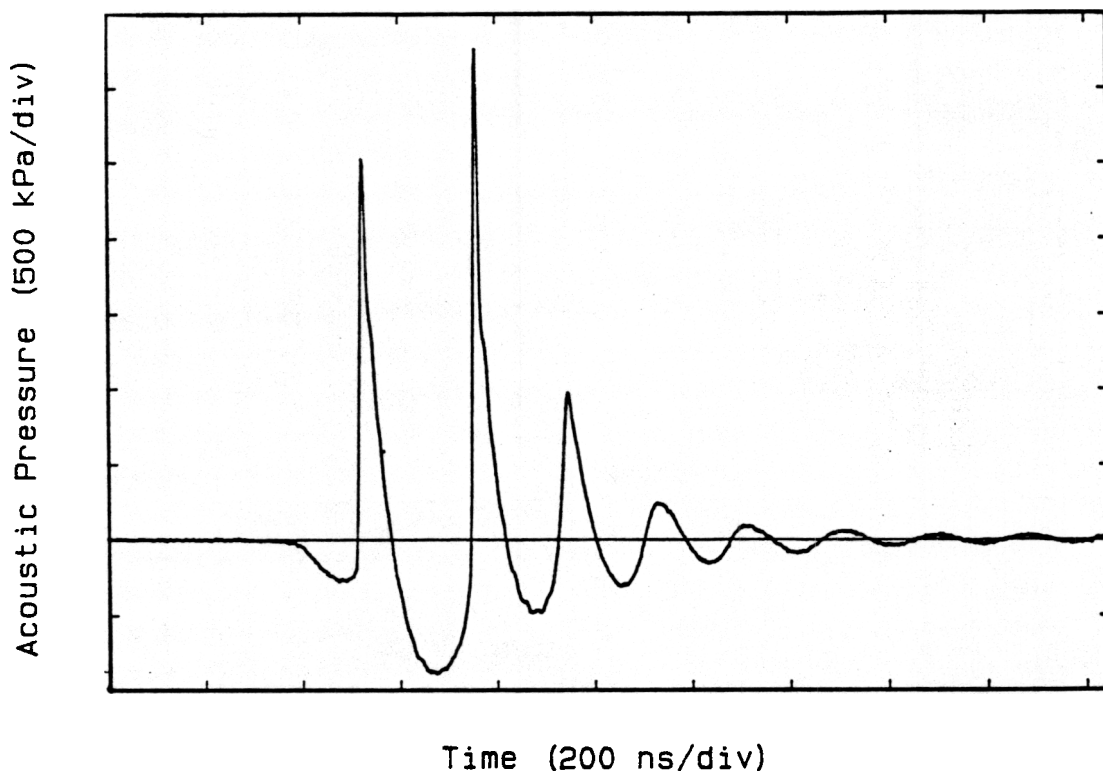


Figure 10.4: Acoustic waveform produced by the 5 MHz transducer (F11941135) used during the nonlinear study, acquired at a distance of 59 mm

RESULTS - COMPARISON OF THEORY AND MEASUREMENT

Raw data

Figure 10.5 gives the raw data obtained for the measurements made on the Perspex sample where, the coefficient RR , given by the ratio of FWE to BWE signals, is presented for transducer-specimen separations covering the range up to 200 mm. It should be noted that, although not shown in this report, the features of the dependence with distance described in Figure 10.5 were also reproduced by measurements made on the cross-linked polystyrene sample.

The ratio RR has been derived for measurements of v_{rms} and v_{fft} , the difference between the two may be attributed to the frequency downshift of the peak in the waveform which affects measurements of rms due to the uncertainty in the frequency of the determined pulse-echo waveform. The peak observed in the value of RR corresponds to the specimen being positioned at the last axial maximum of 52 mm. The low amplitude equivalent value of RR derived from the acoustic properties of the Perspex given in Table 10.3, is 0.15 and is therefore reproduced by the data shown in Figure 10.5 in the limit $z \rightarrow 0$ where the influence of nonlinear distortion is expected to be smaller. A third characteristic of the measurements presented in Figure 10.5, is the stabilisation in values of RR at separation greater than Y_{0+} .

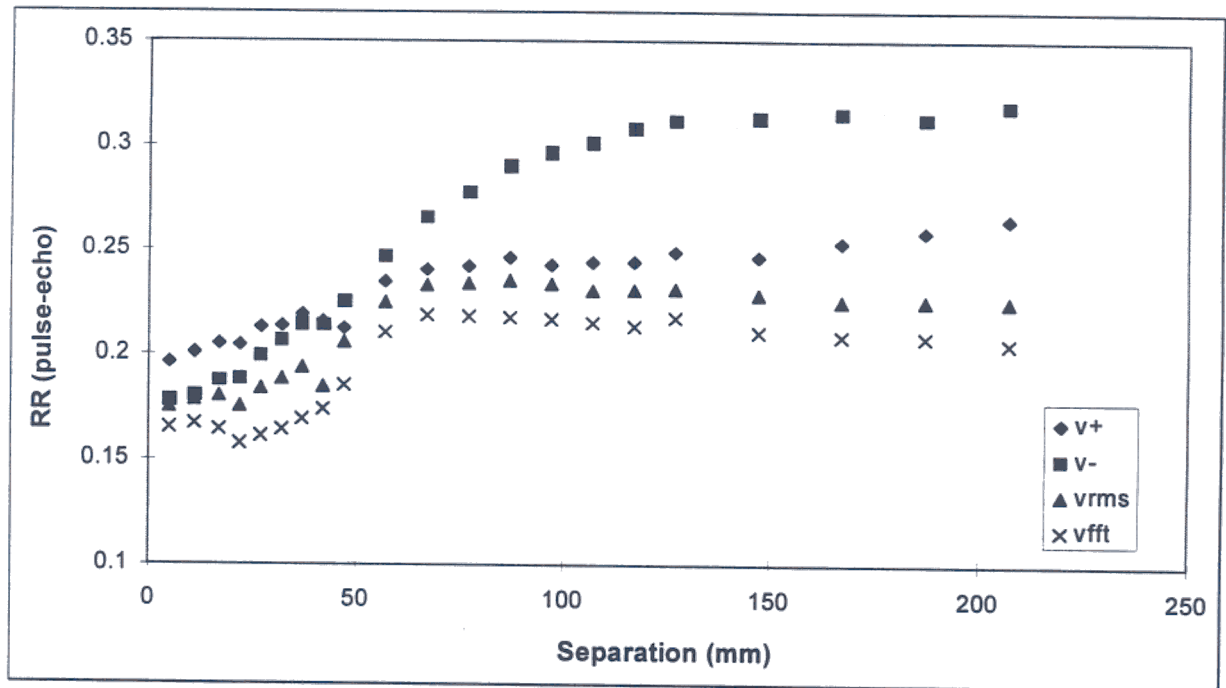


Figure 10.5: Uncorrected FWE-BWE measurements made on the Perspex sample. Values of the reflected amplitude ratio have been derived using various parameters

It is clear from Figure 10.5 that the values of the coefficient RR derived using the parameters v_+ and v_- are very different: these differences arise due to the differing sensitivities of the parameters to diffraction. Consequently, the comparison of predictions and measurements will concentrate on the parameter v_{fft} which provides the narrowband case.

Corrected data

The FWE-BWE measurements, corrected for the effect of diffraction, are shown in Figures

10.6 and 10.7, for the cases of Perspex and cross-linked polystyrene respectively. Here, the normalised coefficient has been derived using the v_{ff} parameter.

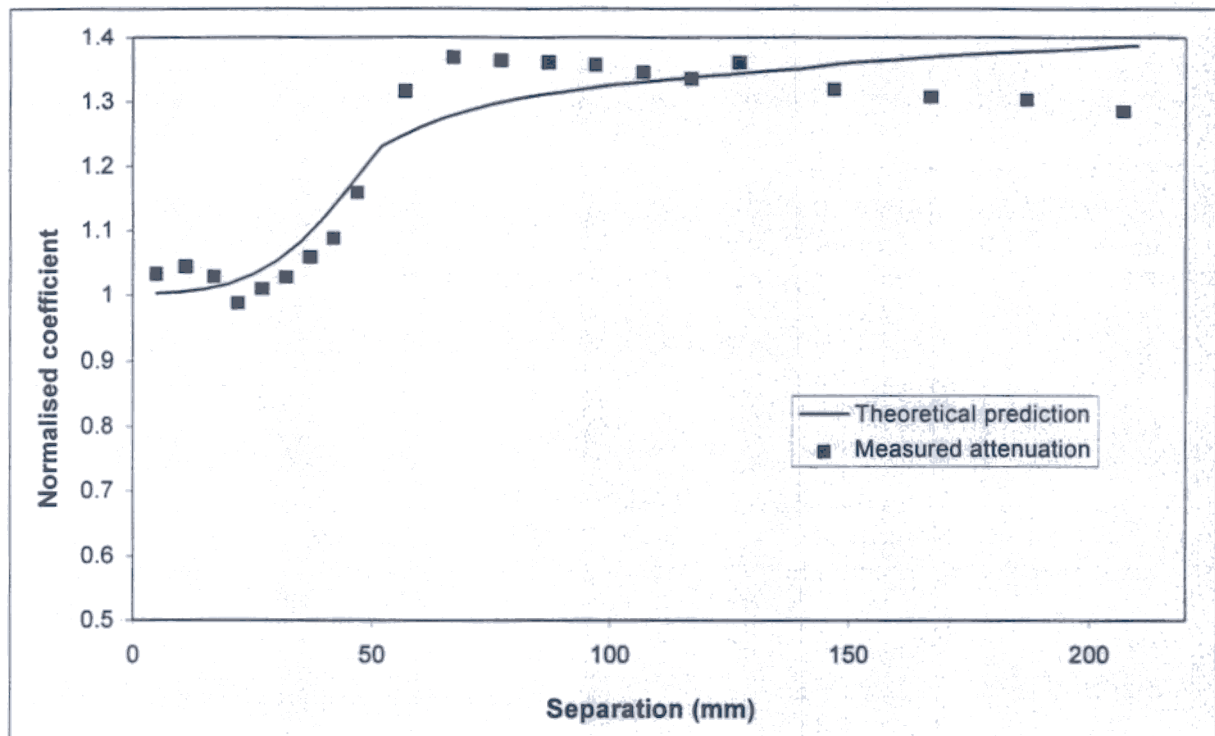


Figure 10.6: Corrected FWE-BWE measurements made on the Perspex sample. Values of the reflected amplitude ratio (RR) have been derived from v_{ff} , and are compared with the results from theoretical calculations

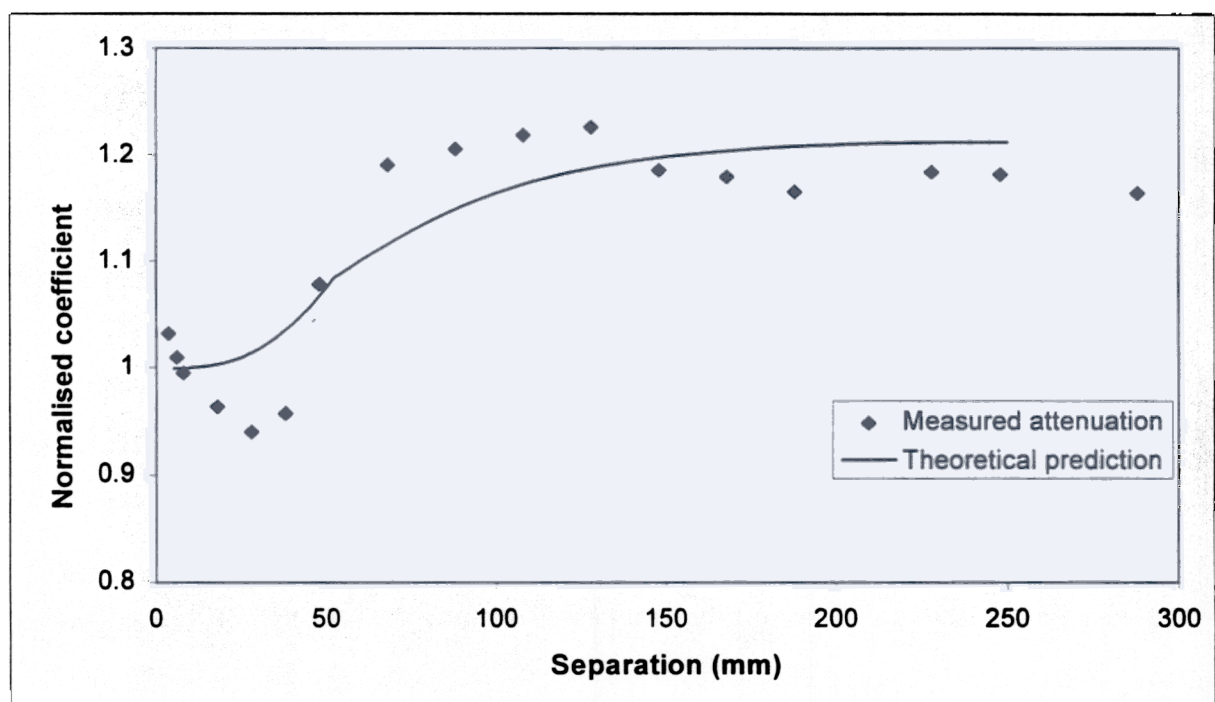


Figure 10.7: Corrected FWE-BWE measurements made on the cross-linked polystyrene sample. Values derive from v_{ff} are compared with the results from theoretical calculations

Also presented on the figures are the dependencies calculated from the MATHCAD model. Due to the use of two different models to cover the cases $z < Y_{0+}$ and $z > Y_{0+}$, a slight cusp is noticeable in the predicted dependence at the position of the last-axial maximum. The predicted dependence has been calculated using an input pressure of 0.9 MPa. Using this pressure the value of the shock parameter (σ) with the specimen positioned at the last axial maximum is only 2.3, so the system studied is not particularly shocked in relation to many of the systems introduced in Section 4 which were focused (Table 4.1). Consequently, the change in measured attenuation arising from the nonlinear effects is only 3 dB. It can be seen that, taken overall, the model reproduces encouragingly the key features of the measurements, in particular the relatively rapid decrease in the measured attenuation with the specimen positioned at the last-axial maximum and beyond this the stabilisation in the value of RR .

10.5 DEMONSTRATION OF NONLINEAR LOSS

The existence of nonlinear loss of the fundamental amplitude in any C-scan configuration may usefully be demonstrated by determining the variation in pulse-echo amplitude after reflection from a 25 mm thick polished stainless steel reflector. Such a reflector may be taken as a reasonable approximation to an ideal reflector. Figure 10.8 shows the raw measurement data derived from the Meccasonics 5 MHz transducer (F11941135), for transducer-specimen separations covering the range 5 mm to 250 mm.

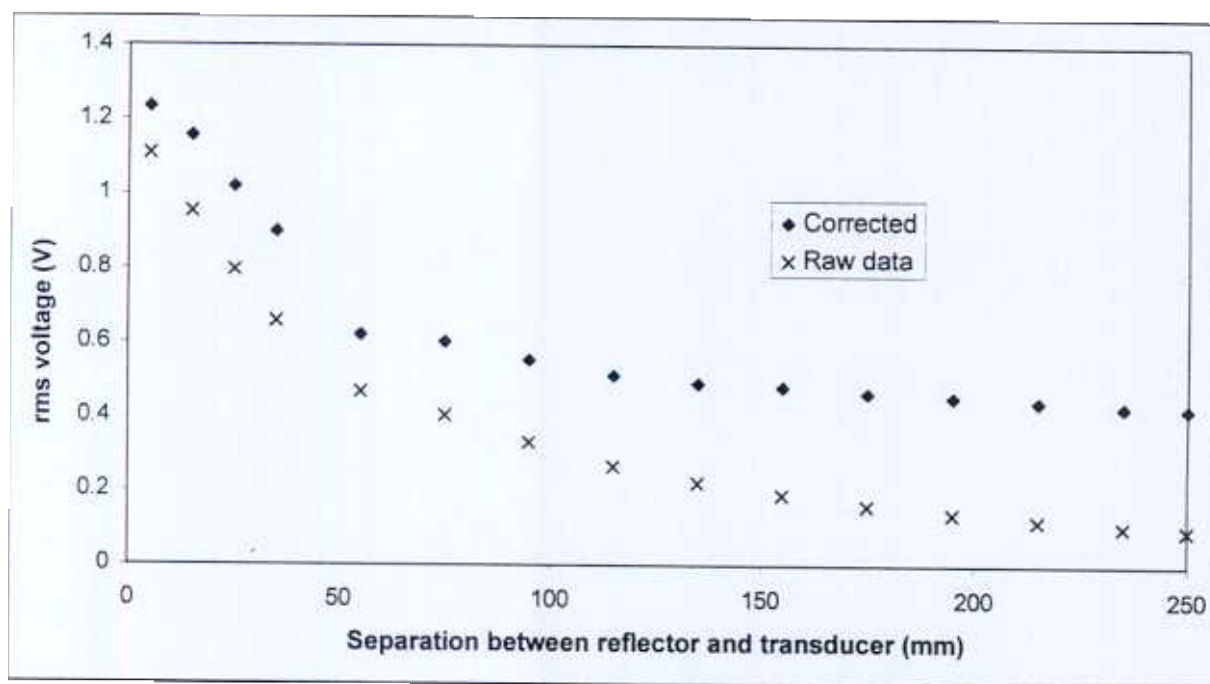


Figure 10.8: Pulse-echo signal-level (*rms*) for the 5 MHz transducer, derived from reflection from a stainless-steel surface. The signal level is plotted as a function of transducer-reflector separation. Corrected data has been adjusted to allow for diffraction and small signal (linear) attenuation in the water medium

At each position the echo was maximised by altering the tilt and rotation of the reflector and determining *rms* voltage at each position. The figure illustrates the rapid fall off in the pulse-echo amplitude of the fundamental, the greatest change occurring in the region $z < 50$ mm. At greater separations, the nonlinear loss stabilises due to the counteracting influence of

small signal absorption and diffraction. The data shown in the Figure 10.8 has been corrected for diffraction, using the model of Williams¹⁰ and for small signal absorption in the water at 5 MHz. The principal features of the significant fall off in signal level are maintained, although the loss at $z < 50$ mm has been mediated slightly.

It should be noted that there is some doubt as to whether application of this diffraction correction is valid at distances close to the transducer face. Indeed, due to the relatively short pulse lengths used, it may be more appropriate to assume that we are working in the plane-wave region of the transducer and use plane-wave theory to derive an estimate of the pressure generated at the face of the transducer from the measured loss.

Extrapolating back to the face of the transducer using the raw data, for Figure 10.8, reveals a nonlinear loss of 1.3 dB for the stainless steel reflector positioned 15 mm from the face of the transducer, corresponding to a σ value at $z = 30$ mm of 1.1. Use of the plane-wave expression for σ gives a value for the peak acoustic pressure amplitude at the face of 1.1 MPa, which, in view of the uncertainties and assumptions that have been used in deriving the value, does show reasonable agreement with the hydrophone derived values. The inference of this result is that pulse-echo measurements of nonlinear loss at distances close to the face of the transducer may potentially be used to estimate the importance of nonlinear propagation in any C-scan configuration, providing the measurements are made using a highly reflective surface such as stainless steel or possibly glass (whose reflection coefficient is close to unity as they are both reasonable approximations to totally reflecting surfaces).

10.6 SUMMARY

A model has been presented which enables the effect of nonlinear distortion incurred during the water propagation path on FWE-BWE C-scan attenuation measurements to be estimated. It has been applied to describe measurements made on specimens of Perspex and cross-linked polystyrene. Agreement between theory and measurement is reasonable, the former reproducing the decrease in attenuation produced due to the increase in the shock parameter, σ , through the last-axial maximum.

It may be possible to assess the importance of nonlinear distortion in any C-scan configuration by estimating the fundamental nonlinear loss in the transducer plane-wave region using reflections from a stainless steel or glass reflector.

11 CONCLUSIONS

Throughout the report, local conclusions have been addressed in the respective Sections. The aim here is to compile these for the specific range of study areas:

NDT systems

it has been established that, at the acoustic pressures and frequencies generated by conventional C-scan inspection equipment, propagation of the acoustic pulse from the transducer to the specimen is a nonlinear process;

- utilising CMAM's unique capability in high resolution and wide-bandwidth membrane hydrophones, the characteristics of the acoustic waveforms generated by a range of systems have been determined: these include acoustically shocked wavefronts, gross asymmetries between the peak-compressional and peak-rarefactional pressures and spectral components in some cases well above 70 MHz, generated by transducers whose nominal frequency of operation is below 10 MHz;

this important finding will be new to the NDT community as conventional pulse-echo measurements are undertaken using band limited systems.

Transducer characterisation

- methods of determining the key acoustical parameters of C-scan transducers such as beamwidths, focal distances and focal depths are conventionally carried out in the field of NDT using small pulse-echo targets which are scanned through the acoustic field. These targets are meant to be approximations to point scatterers;

for unfocused transducers, at positions greater than $0.5 * Y_{0+}$, the ball target is an excellent approximation to a point target. However, for distances closer to the face, a large 'enhanced' response is produced which is extremely sensitive to the position of the ball target on the transducer axis. The response probably arises due to the interaction between the plane and edge-wave components of the piston transducer field and the ball target, and rules out the use of such pulse-echo targets for near-field studies;

- this interaction is not produced during the use of small disc targets (flat-ended rods) so that these may be used to characterise the transducer field at distances closer than $0.5 * Y_{0+}$;
- hydrophones have been shown to give good agreement with pulse-echo techniques for measurements of beamwidths (both axial and cross-axial) provided that the two responses are compared at the -3 dB level (hydrophone) and -6 dB level (pulse-echo), the relationship holding particularly well for unfocused transducers, even for ball target diameters up to 10 mm;

the relationship does not appear to hold so well for focused transducers, where a gradual increase in the measured pulse-echo beamwidth is observed with pulse-echo target size possibly due to the greater importance of spatial-averaging;

- in comparing the beamwidths determined using pulse-echo and hydrophone methods, care must be exercised as the receive bandwidths of the two systems modify the results. Nonlinear propagation results in the generation of higher frequency harmonics which will affect measured beamwidths as these harmonics have a narrower pressure distribution. Low-pass filtering of the broadband hydrophone signal, to isolate the fundamental component, reduces the influence of these harmonics. Even so, it should be noted that pulse-echo measurements of beamwidth may also be affected by the presence of second and possibly higher harmonics;

Collimators

- through a systematic investigation of the effect of collimators on the field of unfocused NDT transducers, collimation effectively produces a smaller transducer whose diameter is equal to the aperture of the collimator;
- these conclusions have been derived from a study of the effect of collimation on the position of the last-axial maximum (Y_{0+}) and on the measured beamwidth in this plane i.e. the effect on the spatial resolution;
- varying the specification of the collimator in terms of its thickness, stand-off distance and diameter to thickness ratio has a negligible effect on the transmitted acoustic pressure distribution;

Materials evaluation

- nonlinear propagation through the water path in a C-scan system results in an enhanced nonlinear loss in the fundamental which may be several orders of magnitude higher than the expected linear absorption loss in water;

this nonlinear loss depends on the pressures generated at the transducer face, whether the transducer is focused or unfocused and the propagation distances involved;

the nonlinear loss severely compromises absolute measurements of material attenuation - a simple model has been developed which considers the FWE-BWE C-scan configuration and the influence of nonlinear loss on the measured attenuation. It has been validated using two reference materials in the field of a 5 MHz unfocused transducer;

- for an unfocused transducer, the nonlinear loss occurring in the transducer field may be investigated by recording the decrease in the reflected signal level from a polished stainless-steel surface as a function of transducer-reflector separation.

12 RECOMMENDATIONS FOR FURTHER WORK

A key requirement for the immediate future is for the results of the research work undertaken to be disseminated widely and effectively to the scientific community. In so doing, the findings will be subjected to wider critical scrutiny. One key mechanism through which this may be done is through publication of the results in learned Journals and presentations of the work at major Conferences.

Furthermore, the fact that nonlinear distortion occurs for the acoustic pulses produced by commercial NDT equipment will be unfamiliar to the NDT community. This information needs to be specially disseminated - future systems may exploit the effect, for example by carrying out second or higher harmonic imaging to provide increased spatial resolution.

The Part 2 : Calibration Procedure needs to be tested out fully to confirm that the procedures specified have the technical rigour for it to be accepted internationally as an ISO Standard.

A pivotal role in this process would be played by completing a:

- transducer round robin, between key test laboratories and manufacturers both nationally and internationally. The experience of carrying through the round robin would improve and optimise the Part 2: Calibration Procedure.

Additionally, it is possible to identify a number of areas of technical work which need to be addressed, providing information which will improve the draft Procedures generated during this project:

- more work needs to be done to investigate beamwidth measurements made on focused transducer fields undertaken using pulse-echo and hydrophone techniques to establish fully the relationship between the measurements. This would probably involve theoretical analysis;

the origin of the enhanced response obtained close to the face of transducers for measurements made using ball targets should be investigated further;

- the frequency range given in the Scope was restricted from 0.5 to 10 MHz and this reduced the likely influence of frequency downshift on measurements. Any extension of the Standard to higher frequencies would require the development and validation of alternative methods, such as those given in the ASTM document, which seek to minimise the effect of frequency downshift;
- it is clear from the work reported both here and by DERA that nonlinear loss of the fundamental frequency component provides an important contribution to the uncertainty in the measurement of absolute attenuation. The theoretical modelling work needs to be extended to cover alternative C-scan configurations and needs to be supported by careful measurements, some of which will involve characterising the acoustic waveform at various positions in the acoustic field. Simple methods, appropriate for use at an industrial level, need to be developed in which the existence and importance of nonlinear distortion in any measurement configuration might be assessed.

13 ACKNOWLEDGEMENTS

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APPENDIX A: Meccasonics transducer hydrophone reference data sheet.

Serial number: F01951172

Crystal diameter: 15 mm

Nominal centre frequency: 1 MHz

Nominal focal length: 50 mm

Measured values:

Parameter	Value	
-3 dB centre frequency (MHz)	5.5	
-3 dB frequency bandwidth	8%	
Peak frequency (MHz)	5.60	
Peak-positive pressure (kPa)	970	
Peak-negative pressure (kPa)	-770	
-3 dB beamwidth (mm)	p_+	0.55
	p_-	1.35
	$ppsi$	1.20
Focal length (mm)	p_+	57
	p_-	50
	$ppsi$	51
-3 dB depth of focal zone (mm)	p_+	35
	p_-	31
	$ppsi$	45

APPENDIX A: Meccasonics transducer hydrophone reference data sheet.

Serial number: F1657

Crystal diameter: 15 mm

Nominal centre frequency: 1 MHz

Nominal focal length: unfocused

Measured values:

Parameter	Value	
-3 dB centre frequency (MHz)	1.14	
-3 dB frequency bandwidth	32%	
Peak frequency (MHz)	1.16	
Peak-positive pressure (kPa)	196	
Peak-negative pressure (kPa)	-191	
-3 dB beamwidth (mm)	p_+	4.00
	p_-	6.25
	$ppsi$	5.05
Y_{0+} (mm)	p_+	46
	p_-	42
	$ppsi$	42
-3 dB aperture size (mm)	p_+	12.8
	p_-	9.6
	$ppsi$	8.4
Beam divergence	3.8°	

APPENDIX A: Meccasonics transducer hydrophone reference data sheet.

Serial number: F01951173

Crystal diameter: 10 mm

Nominal centre frequency: 2.5 MHz

Focal length: 50 mm

Measured values:

Parameter	Value	
-3 dB centre frequency (MHz)	3.31	
-3 dB frequency bandwidth	39%	
Peak frequency (MHz)	3.33	
Peak-positive pressure (MPa)	6.6	
Peak-negative pressure (MPa)	-2.0	
-3 dB beamwidth (mm)	p_+	0.79
	p_-	2.12
	$ppsi$	1.30
Focal length (mm)	p_+	54
	p_-	44
	$ppsi$	50
-3 dB depth of focal zone (mm)	p_+	19.5
	p_-	30
	$ppsi$	35

APPENDIX A: Meccasonics transducer hydrophone reference data sheet.

Serial number: F1655

Crystal diameter: 10 mm

Nominal centre frequency: 2.5 MHz

Nominal focal length: unfocused

Measured values:

Parameter	Value	
-3 dB centre frequency (MHz)	2.43	
-3 dB frequency bandwidth	76%	
Peak frequency (MHz)	2.70	
Peak-positive pressure (MPa)	1.0	
Peak-negative pressure (MPa)	-0.60	
-3 dB beamwidth (mm)	p_+	4.00
	p_-	6.25
	$ppsi$	5.05
Y_{0+} (mm)	p_+	40
	p_-	36
	$ppsi$	38
-3 dB aperture size (mm)	p_+	9.6
	p_-	12.8
	$ppsi$	8.2
Beam divergence	3.8°	

APPENDIX A: Meccasonics transducer hydrophone reference data sheet.

Serial number: F01951170

Crystal diameter: 10 mm

Nominal centre frequency: 5 MHz

Nominal focal length: 50 mm

Measured values:

Parameter	Value	
-3 dB centre frequency (MHz)	3.81	
-3 dB frequency bandwidth	74%	
Peak frequency (MHz)	3.9	
Peak-positive pressure (MPa)	3.6	
Peak-negative pressure (MPa)	-1.4	
-3 dB beamwidth (mm)	<i>p+</i>	0.70
	<i>p-</i>	2.25
	<i>ppsi</i>	1.60
Focal length (mm)	<i>p+</i>	46
	<i>p-</i>	33
	<i>ppsi</i>	41
-3 dB depth of focal zone (mm)	<i>p+</i>	47
	<i>p-</i>	55
	<i>ppsi</i>	65

Note: these reference measurements made prior to transducer repair.

APPENDIX A: Meccasonics transducer hydrophone reference data sheet.Serial number: **F11941135**

Crystal diameter: 10 mm

Nominal centre frequency: 5 MHz

Nominal focal length: Unfocused

Measured values:

Parameter	Value	
-3 dB centre frequency (MHz)	4.72	
-3 dB frequency bandwidth	37%	
Peak frequency (MHz)	4.81	
Peak-positive pressure (MPa)	3.3	
Peak-negative pressure (MPa)	-0.9	
-3 dB beamwidth (mm)	<i>p+</i>	1.35
	<i>p-</i>	4.00
	<i>ppsi</i>	2.40
Y_{0+} (mm)	<i>p+</i>	60
	<i>p-</i>	53
	<i>ppsi</i>	59
-3 dB aperture size (mm)	<i>p+</i>	7.1
	<i>p-</i>	7.0
	<i>ppsi</i>	7.0
Beam divergence	3.7 °	

APPENDIX A: Meccasonics transducer hydrophone reference data sheet.

Serial number: F10941099

Crystal diameter: 10 mm

Nominal centre frequency: 10 MHz

Nominal focal length: 50 mm

Measured values:

Parameter	Value	
-3 dB centre frequency (MHz)	10.3	
-3 dB frequency bandwidth	65%	
Peak frequency (MHz)	8.7	
Peak-positive pressure (MPa)	2.90	
Peak-negative pressure (MPa)	-0.70	
-3 dB beamwidth (mm)	p_+	0.95
	p_-	1.25
	$ppsi$	1.0
Focal length (mm)	p_+	52
	p_-	51
	$ppsi$	53
-3 dB depth of focal zone (mm)	p_+	26
	p_-	24
	$ppsi$	32

High band drive setting on Meccasonics unit.

APPENDIX A: Meccasonics transducer hydrophone reference data sheet.

Serial number: F1658

Crystal diameter: 10 mm

Nominal centre frequency: 10 MHz

Nominal focal length: unfocused

Measured values:

Parameter	Value	
-3 dB centre frequency (MHz)	7.1	
-3 dB frequency bandwidth	45%	
Peak frequency (MHz)	7.77	
Peak-positive pressure (kPa)	380	
Peak-negative pressure (kPa)	-260	
-3 dB beamwidth (mm)	<i>p+</i>	1.56
	<i>p-</i>	5.65
	<i>ppsi</i>	3.28
Y_{0+} (mm)	<i>p+</i>	165
	<i>p-</i>	125
	<i>ppsi</i>	140
-3 dB aperture size (mm)	<i>p+</i>	8.78
	<i>p-</i>	9.05
	<i>ppsi</i>	9.05

High band drive setting on Meccasonics unit.

APPENDIX B: Hydrophone measurement data sheet for DERA-loaned flaw detector.

Serial number: 001401

Crystal diameter: 9.53 mm

Nominal centre frequency: 10 MHz

Nominal focal length: 76 mm

Measured values:

Parameter	Value	
-3 dB centre frequency (MPa)	7.6 MHz	
-3 dB frequency bandwidth	76%	
Peak frequency (MHz)	7.2	
Peak-positive pressure (MPa)	1.80	
Peak-negative pressure (MPa)	-1.0	
-3 dB beamwidth (mm)	<i>p+</i>	0.65
	<i>p-</i>	1.85
	<i>ppsi</i>	1.16
Focal length (mm)	<i>p+</i>	69
	<i>p-</i>	63
	<i>ppsi</i>	65.5
-3 dB depth of focal zone (mm)	<i>p+</i>	33
	<i>p-</i>	>40
	<i>ppsi</i>	>60

APPENDIX B: Hydrophone measurement data sheet for DERA-loaned flaw detector.

Serial number: "10F"

Crystal diameter: 9.53 mm

Nominal centre frequency: 10 MHz

Nominal focal length: 38 mm

Measured values:

Parameter	Value	
-3 dB centre frequency (MHz)	9.07	
-3 dB frequency bandwidth	45%	
Peak frequency (MHz)	8.7	
Peak-positive pressure (MPa)	10.5	
Peak-negative pressure (MPa)	-3.6	
-3 dB beamwidth (mm)	p_+	0.30
	p_-	0.65
	$ppsi$	0.45
Focal length (mm)	p_+	36
	p_-	32
	$ppsi$	34
-3 dB depth of focal zone (mm)	p_+	-
	p_-	12.5
	$ppsi$	11.9

APPENDIX B: Hydrophone measurement data sheet for DERA-loaned flaw detector.

Serial number: 007406

Crystal diameter: 12.7 mm

Nominal centre frequency: 5 MHz

Nominal focal length: unfocused

Measured values:

Parameter	Value	
-3 dB centre frequency (MHz)	4.98	
-3 dB frequency bandwidth	54%	
Peak frequency (MHz)	4.79	
Peak-positive pressure (kPa)	540	
Peak negative pressure (kPa)	-500	
-3 dB beamwidth (mm)	<i>p+</i>	5.13
	<i>p-</i>	6.77
	<i>ppsi</i>	5.00
Y_{0+} (mm)	<i>p+</i>	178
	<i>p-</i>	116
	<i>ppsi</i>	150
-3 dB aperture size (mm)	<i>p+</i>	11.6
	<i>p-</i>	11.8
	<i>ppsi</i>	11.63

"High" drive setting.

APPENDIX B: Hydrophone measurement data sheet for DERA-loaned flaw detector.

Serial number: D12559

Crystal diameter: 12.7 mm

Nominal centre frequency: 2.25 MHz

Nominal focal length: unfocused

Measured values:

Parameter	Value	
-3 dB centre frequency (MHz)	2.45	
-3 dB frequency bandwidth	51%	
Peak frequency (MHz)	2.50	
Peak-positive pressure (kPa)	440	
Peak-negative pressure (kPa)	-400	
-3 dB beamwidth (mm)	<i>p+</i>	1.52
	<i>p-</i>	4.06
	<i>ppsi</i>	3.50
Y_{0+} (mm)	<i>p+</i>	70
	<i>p-</i>	64
	<i>ppsi</i>	66
-3 dB aperture size (mm)	<i>p+</i>	11.90
	<i>p-</i>	11.38
	<i>ppsi</i>	11.39

"High" drive setting.

APPENDIX C: TRANSDUCER FIELD PROPERTIES

IMPORTANT SPATIAL CHARACTERISTICS OF TRANSDUCER FIELDS

A wealth of technical literature exists which describes the distribution of pressure amplitude generated from both unfocused (normally termed plane-piston) transducers and focused transducers. A comprehensive description is given in Gooberman (C1), but the most crucial points are picked out here. The aim of this Appendix is to present some simple relationships which, using nominal values for the transducer parameters, may be used to provide information on the spatial distribution of ultrasound, both along the beam-alignment axis and perpendicular to it. The information will provide guidance on the required spatial resolution for transducer characterisation measurements as embodied in the Part 2: Calibration Procedure document. It is anticipated that the nominal values of parameters such as piezoelectric crystal active element diameter, the radius of curvature for a focusing transducer and nominal frequency will be known.

The validity of the expressions depends on how closely the vibration of the active surface of the crystal approaches the piston-like vibration assumed in the models used. They are also strictly only appropriate for narrow-band (discrete frequency) operation, but they represent a reasonable approximation provided the bandwidth is less than 60%.

THE FIELD OF AN UNFOCUSED (PLANE-PISTON) TRANSDUCER

The axial pressure field produced by an ultrasonic transducer is characterised by a series of maxima and minima which arise due to diffractive interference. The position of the last axial maximum, N_{nom} , is an important quantity and if a_t is the radius of the transducer active element and λ the wavelength, it is given by:

$$N_{nom} = a_t^2 / \lambda \quad (C1)$$

here, λ is given by c/f , where c is the propagation speed of ultrasound at the temperature of the propagation medium and f is the frequency. Axial separation distances greater than N_{nom} are denoted as being in the far field of the transducer (the Fraunhofer region), and in this region, the acoustic pressure at a point Q, denoted P_Q , is given by:

$$P_Q = \frac{P' \pi a_t^2}{r} e^{i(\omega t - kr)} \left[\frac{2J_1(ka_t \sin \theta)}{ka_t \sin \theta} \right]$$

where P' is proportional to the pressure at the piston face, r is the distance from the centre of the transducer, k is the wavenumber (equal to $2\pi/\lambda$), ω is the angular frequency ($\equiv 2\pi f$), θ is the angle subtended between a line connecting the centre of the piston and the point Q, and the normal to the piston, and J_1 is a Bessel function of the first kind. The term in square brackets represents the directivity function: it gives the variation in pressure with direction, and the remaining terms describe the variation in pressure along the normal passing through the centre of the piston.

The Bessel function expression may be used to derive the following relationship for the -3 dB pressure beamwidth at N_{nom} :

$$\text{- 3 dB pressure beam - width} = 0.5136 a_t \quad (C2)$$

A fundamental difference exists in beamwidth measurements made using hydrophone and pulse-echo techniques. If we first consider the case of a hydrophone, assuming the device is omnidirectional (and therefore behaving as a point receiver) its use in scanning the acoustic field will determine the transmit directivity of the transducer.

Now turning to the pulse-echo case, assuming that the reflecting target is an infinitesimally small point, the resultant pulse-echo response of the transducer to a target moved through the field is a convolution of its transmit and receive responses. Assuming, through reciprocity, that these responses are equal, the pulse-echo response will decrease as the square of the Bessel function as the target is moved radially perpendicular to the acoustic axis. In principle, therefore, deriving beamwidth data from measurements made using hydrophones at the -3 dB level (the off-axis distance to be moved for a fall in the signal to a prescribed level) should be equivalent to pulse-echo derived values expressed at the -6 dB level. This basic relationship is assumed in the ASTM E 1065-92 Standard (C2).

C.3 THE FIELD OF A FOCUSED PLANE-PISTON TRANSDUCER

The theoretical treatment of focused transducers is somewhat more complex, but a simple assessment will be provided here. Focusing is commonly brought about by either shaping the active element of the transducer or by fitting a suitable refracting lens. In either case, the important quantity which determines the pressure distribution in the acoustic field is the radius of curvature of the active face. Due to diffraction, the position of the focal point and the centre of curvature are not quite coincident, although for the purposes of this document they will assumed to be so.

Focusing behaviour may then be estimated from a knowledge of the frequency, the radius of curvature of the transducer (taken to be equal to the focal distance, Y_F) and the radius of the active element (a_t). As in the case of unfocused transducers, the distribution of acoustic pressure both along and perpendicular to the beam alignment axis is of interest.

C.3.1 Focal zone (or focal depth)

The extent of the focal zone (or focal depth) is an important quantity, as it dictates the positioning of a test specimen in the field of a transducer for a C-scan. The following expression may be used to estimate the depth of the focal zone and adjust the scan increment of the -6 dB pulse-echo axial profile according to Equation (C3) below:

$$Y_{FZ} = \frac{Y_F^2}{N_{nom}} \cdot \frac{2}{1 + 0.5 \left(\frac{Y_F}{N_{nom}} \right)} \quad (C3)$$

Here, N_{nom} is again given by a_t^2/λ and is the last-axial maximum distance for an unfocused transducer of equivalent radius and frequency. For reasons identical to those discussed above for the cross-axial case, the on-axis spatial variation of a focused transducer produced through use of a pulse-echo target is effectively the square of that measured using a

hydrophone. This hence forms the basis of the -3 dB/-6 dB comparison applicable also to measurements of the focal zone of transducers.

C.3.2 Focal beamwidths

The distribution of pressure in the plane perpendicular to the beam-alignment axis is again determined by a Bessel function expression. Table C1 gives a summary of estimated values of the -6 dB pulse-echo beamwidth presented as a function of the focal distance and the product ka_t . Values of Y_F and k could be nominal or may come from measurements of the pulse-echo axial profile and the pulse-echo frequency response (or equivalent measurements for the hydrophone case). The values given in Table C1 should only be regarded as approximate values. Nonlinear effects occurring during propagation mentioned in Section 4 can cause strong broadening of the fundamental pressure amplitude, such that the observed value may appear greater than those appearing in Table C1. The values may therefore be regarded as worst case estimates.

Y_F	Value of ka_t										
	10	20	40	60	80	100	120	140	160	180	200
20	6.5	3.24	1.62	1.08	0.8	0.65	0.54	0.46	0.41	0.36	0.32
25	8.1	4.1	2.03	1.35	1.0	0.81	0.68	0.58	0.51	0.45	0.41
30	9.7	4.9	2.4	1.62	1.22	0.97	0.8	0.69	0.61	0.54	0.49
35	11.3	5.7	2.84	1.89	1.42	1.13	0.95	0.81	0.71	0.63	0.57
40	13	6.5	3.2	2.16	1.62	1.3	1.08	0.93	0.81	0.72	0.65
45	14.6	7.3	3.65	2.43	1.82	1.46	1.22	1.04	0.91	0.81	0.73
50	16.2	8.1	4.1	2.7	2.0	1.62	1.35	1.16	1.01	0.9	0.81
55	17.8	8.9	4.5	3	2.2	1.78	1.49	1.27	1.11	1.0	0.89
60	19.4	9.7	4.9	3.24	2.4	1.9	1.62	1.39	1.22	1.08	0.97
65	21.1	10.5	5.3	3.5	2.6	2.1	1.76	1.5	1.32	1.17	1.05
70	22.7	11.3	5.7	3.8	2.8	2.3	1.9	1.62	1.42	1.26	1.13

Table C.1: Values for the -6 dB pulse-echo beamwidth (given in mm) for focused transducers. Values are presented as a function of the nominal focal distance of the transducer (Y_F) and the product ka_t . These are equivalent to the -3 dB beamwidth determined using a hydrophone.

C.4 THE PLANE AND EDGE-WAVE TREATMENT OF A PLANE-PISTON FIELD

In many situations it is useful to consider the acoustic field of a plane-piston transducer as being comprised of two distinct components. These are a plane-wave component which originates from the face of the transducer and an edge-wave which travels from the rim of the transducer. The two components are 180 ° out of phase and it is the interference of these two

which gives rise to the diffractive structure occurring within the piston field. The concept is illustrated in Figure C.1.

A number of observations may be appropriately made. With the measurement point on the axis, the edge-wave will arrive coherently. Moving the measurement point off axis will leave the plane-wave component unchanged but will destroy the edge-wave coherence. At measurement positions close to the transducer, providing the pulse lengths are short enough, the two components can be resolved out in time, due to the difference in their respective path lengths and therefore propagation times to the measurement point of interest. In the far field of the transducer, the two components will coalesce, and when the path difference between the two is equal to $\lambda/2$, they interfere constructively to yield the last axial maximum.

The basic plane and edge-wave concept is useful in deriving an understanding of the ultrasonic field and is applied within this report in Sections 6 and 8 and Appendix E.

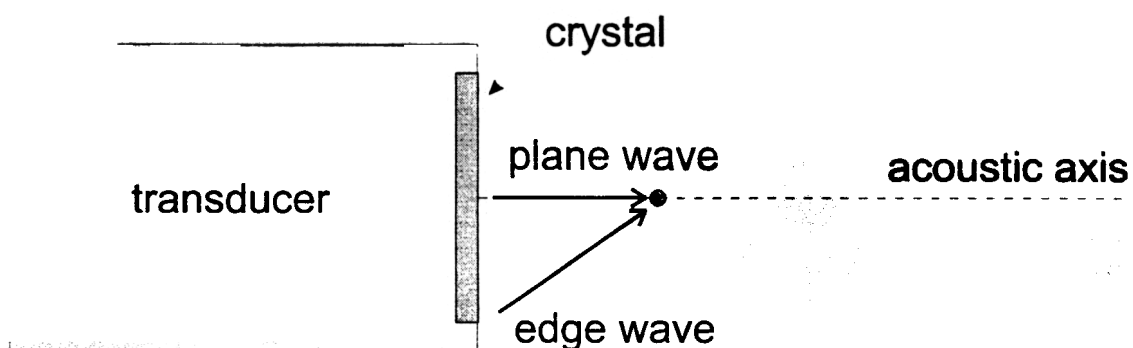


Figure C.1: Schematic diagram of plane-wave and edge-wave components

C.5 REFERENCES

- C1 GOOBERMAN, G.L. Ultrasonics Theory and Application, 1968, English Universities Press Limited, London, pp 27-36.
- C2 ASTM E 1065-92: Standard guide for evaluating characteristics of ultrasonic search units.

APPENDIX D: THE ACOUSTIC WAVEFORM AND DERIVED PARAMETERS

BACKGROUND

This Appendix illustrates the way in which various acoustic parameters of interest may be derived from hydrophone measurements of the acoustic pulses generated by NDT transducers. It is assumed that the absolute sensitivity of the hydrophone is known (usually expressed in nV Pa^{-1}).

WAVEFORM ANALYSIS

The output from the preamplifier used in hydrophone-based beam plotting measurements is fed to a digitising oscilloscope, producing a screen image such as that seen in Figure D.1.

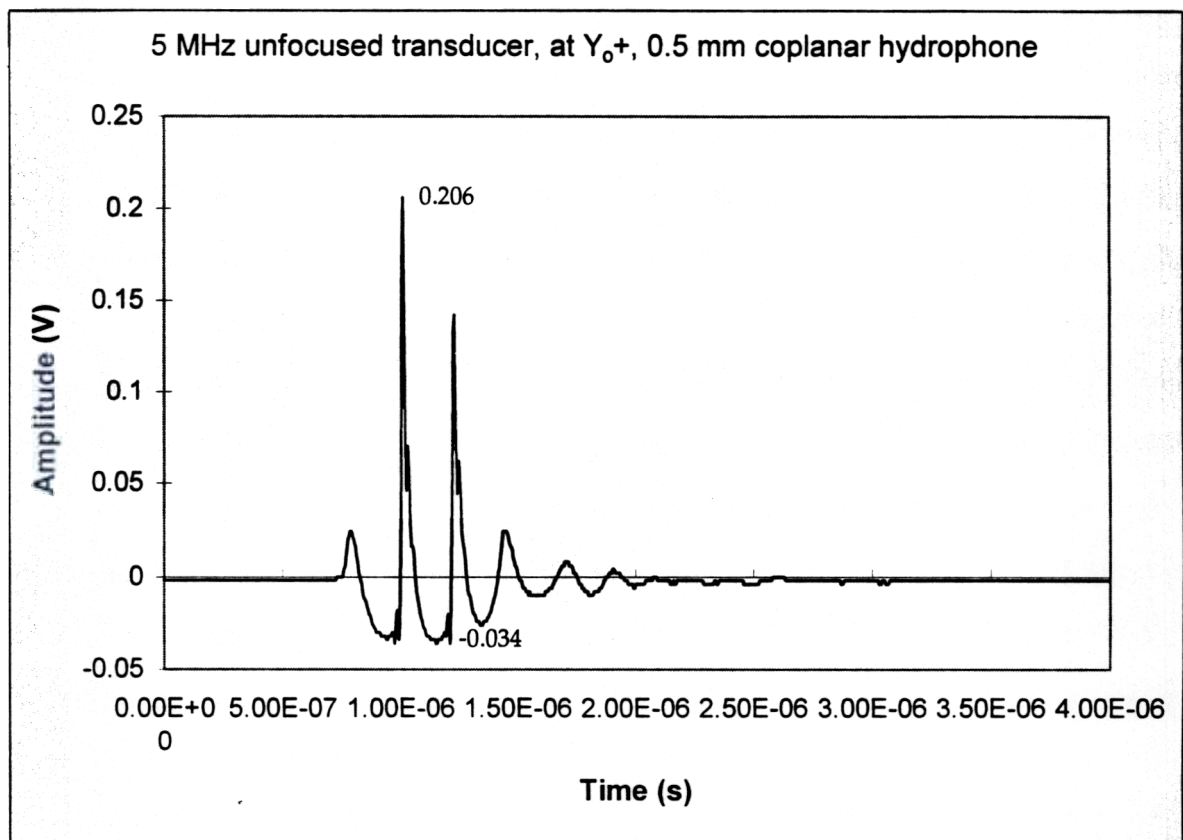


Figure D.1: Hydrophone-measured acoustic pulse, as seen on digital oscilloscope. The maximum and minimum voltage values are shown

From the levels of maximum and minimum voltage read from the oscilloscope, the values of the **peak-positive acoustic pressure** (p_+) and **peak-negative acoustic pressure** (p_-) in the pulse may be derived from the combined hydrophone-amplifier sensitivity (at the centre frequency of the field measured). The voltage values noted on Figure D.1 correspond to p_+ and p_- values of 2.32 MPa and -0.38 MPa respectively. In hydrophone scans, plots of acoustic pressure distributions as a function of space are derived. It is clear that there is significant asymmetry in the acoustic pulse shown in Figure D.1: this is due to diffraction and the nonlinear propagation occurring between the transducer and the hydrophone, which generates higher harmonics of the fundamental frequency, and the broad bandwidth of the

hydrophone is able to detect these components. Performing an FFT on the data results in the trace seen in Figure D.2.

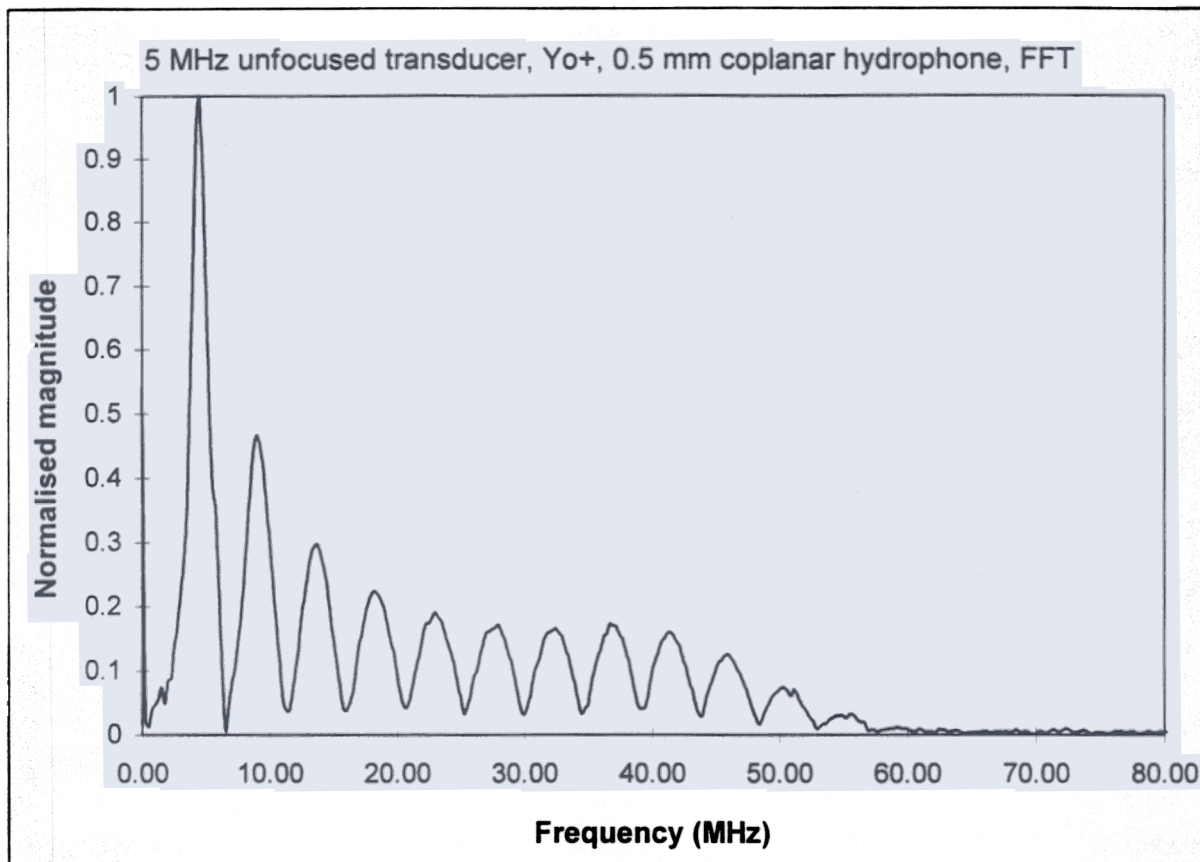


Figure D.2: FFT of acoustic waveform seen in Figure D.1

The effect of nonlinear distortion may be seen in the number of higher frequency components. These fall away above 55 MHz, due to the -6 dB bandwidth of the amplifier (45 MHz). Measurements made using larger bandwidth systems on the same transducer have shown that there are components in excess of 75 MHz. The **peak frequency** is 4.50 MHz, the **-3 dB bandwidth** is 22%, and the **-3 dB centre frequency** is also 4.5 MHz.

The acoustic pressure waveform may be used in the derivation of many further terms. One parameter which is of particular interest is the **pulse pressure-squared integral**, *ppsi*. This is defined as the time integral of the square of the instantaneous acoustic pressure in the pulse, integrated over the whole of the pulse. It is determined from the square of the acoustic pressure waveform, and is an expression of the time-integrated energy in the pulse.

The parameter is of interest in NDT fields because it tends to be less sensitive to nonlinear effects, and is hence more directly comparable to the data obtained from pulse-echo measurements, such as the pulse energy. As with acoustic pressure, the value of *ppsi* (or the voltage equivalent) may be calculated at each measurement point in a scan, building up its spatial distribution. Figure D3 shows the pulse pressure-squared integral calculated from the waveform in Figure D1. The final value of the pulse pressure-squared integral is calculated, and this is then used in spatial plots. When performing spatial measurements of the transducer field, three different parameters may be used, p_+ , p_- , and *ppsi*. Values for

beamwidths etc. for all these parameters, which are typically different for each of them, were derived for the reference data, which can be found in Appendices A and B.

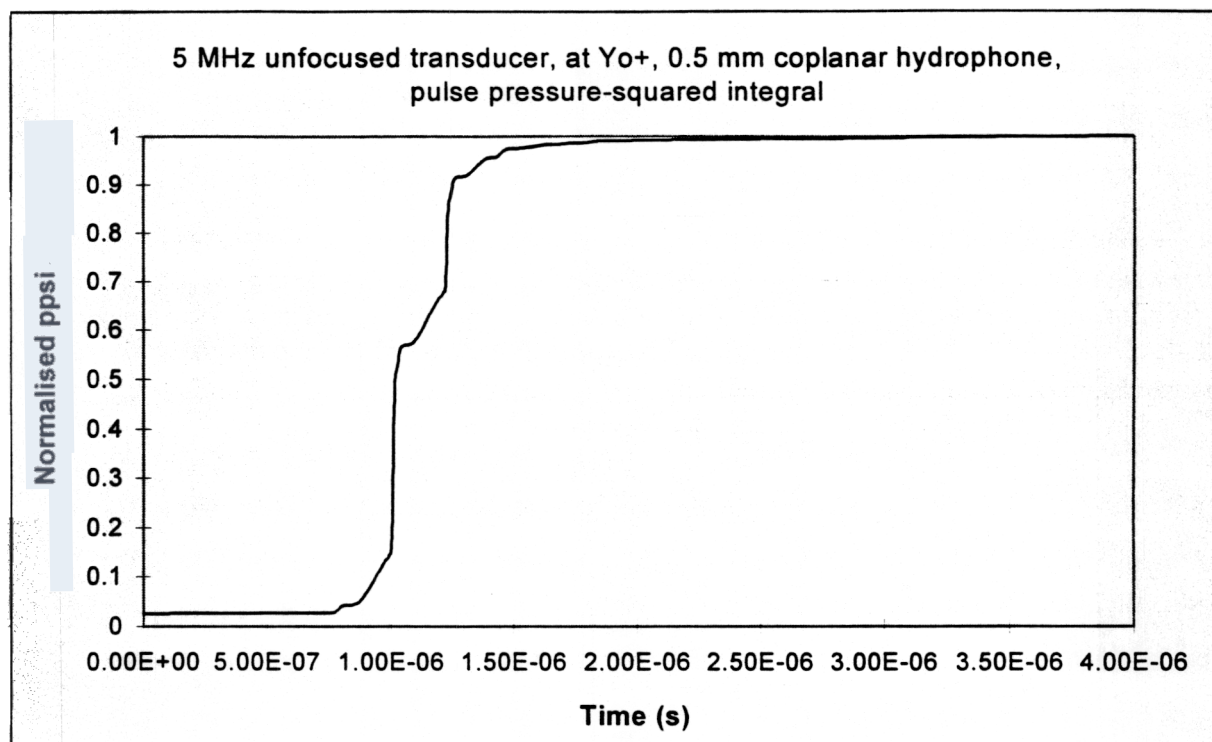


Figure D.3: Plot of pulse pressure-squared integral (*ppsi*) calculated from the acoustic waveform in shown in Figure D.1.

D.3 NONLINEAR PROPAGATION

The degree of non-linearity of an acoustic pulse may be quantified in terms of the non-linearity propagation parameter σ_m , defined as the “index which permits the prediction of nonlinear distortion of ultrasound for a specified ultrasonic transducer” (International Electrotechnical Commission, IEC 1102: 1991, Measurement and characterisation of ultrasonic fields using hydrophones in the frequency range 0.5 MHz to 15 MHz):

$$\sigma_m = \frac{\beta \omega l_1}{\rho c^3} p_m \frac{1}{(F_g - 1)^{1/2}} \ln((F_g - 1)^{1/2} + F_g^{1/2})$$

where ρ is the density of the medium, c is the propagation speed of ultrasound in the medium, β is the nonlinearity parameter ($\beta = 1 + B/2A = 3.5$ for pure water at 20 °C), ω is the angular frequency, l_1 is the distance from the face of the ultrasonic transducer to the plane containing the point of spatial-peak temporal-peak acoustic pressure, F_g is 0.69 times the ratio of the geometrical area of the ultrasonic transducer to the -6 dB beam area, and p_m is the mean peak-cycle acoustic pressure at the point in the acoustic field corresponding to the spatial-peak temporal-peak acoustic pressure, and is equal to the arithmetic mean of p_+ and p_- . This equation was used to calculate the values of σ_m provided in Section 4.3.1 for the focused transducers studied.

APPENDIX E: CONSIDERATIONS OF SMALL PULSE-ECHO TARGET AND HYDROPHONE DIMENSIONS

E.1 BACKGROUND

Section 2 of this report presented an overview of relevant Standards and within these, specifications were given for the dimensions of the pulse-echo target and hydrophone to be used during transducer characterisation. For ball targets commonly used in NDT for beam parameter measurements, this translates to diameters between 5λ and 10λ . For hydrophone dimensions, the equivalent maximum diameters are 2λ (ASTM E1065-92) and 0.5λ (Panametrics guidance document). Presenting the specification in this way, in terms of a number of wavelengths, may make the criterion too difficult to achieve in certain situations, perhaps unnecessarily so. Taking a frequency of 10 MHz, the requirement can only be met by using a small ball target of diameter 1.5 mm and a hydrophone diameter of 0.3 mm, the latter in particular being difficult to achieve.

One of the goals of this study was to investigate these specifications to ascertain whether they were too restrictive and if they could be relaxed to any extent. It may be more appropriate to describe the specification of both pulse-echo targets and hydrophones in terms of the acoustic beamwidths at the particular measurement site of interest. Guideline values for these beamwidths may be derived from simple relationships of the type given in Appendix C.

In order to support this approach, there is a need to estimate the effect of spatial-averaging of pressure over the detector (either a hydrophone or small target when the transducer is operated in pulse-echo mode) at the field point of interest, to ensure that its effect on the parameters of interest (principally beamwidths determined at Y_0 or the focus) is maintained below a specific level. The effect of spatial-averaging has been investigated for the following measurement configurations:

small ball targets;
small disc targets;
hydrophones.

Small pulse-echo targets are meant to provide approximations to infinitesimally small point-like targets placed in the acoustic field. It is therefore useful to initially consider and understand the response of a pulse-echo transducer to such an idealized though physically unrealisable target. This will aid in interpreting the response obtained from more practical targets.

E.2 IDEALISED RESPONSE OF A TRANSDUCER OPERATED IN PULSE-ECHO MODE TO A POINT TARGET

The treatment given here originates from the publication by Weight and Hayman (E1) whose paper dealt with the reflection of short-duration ultrasonic pulses from small targets. The paper specifically uses the established plane and edge-wave treatment of the plane-piston transducer acoustic field covered in Appendix C, in considering the response of such a transducer to a point reflector.

Figure E.1 depicts the configuration of interest, with the point target aligned on the acoustic axis of the transducer. The scattered spherical field from the target comprises two components:

one is the plane-wave component originating from the surface of the transducer, the second is the edge-wave which propagates from its periphery.

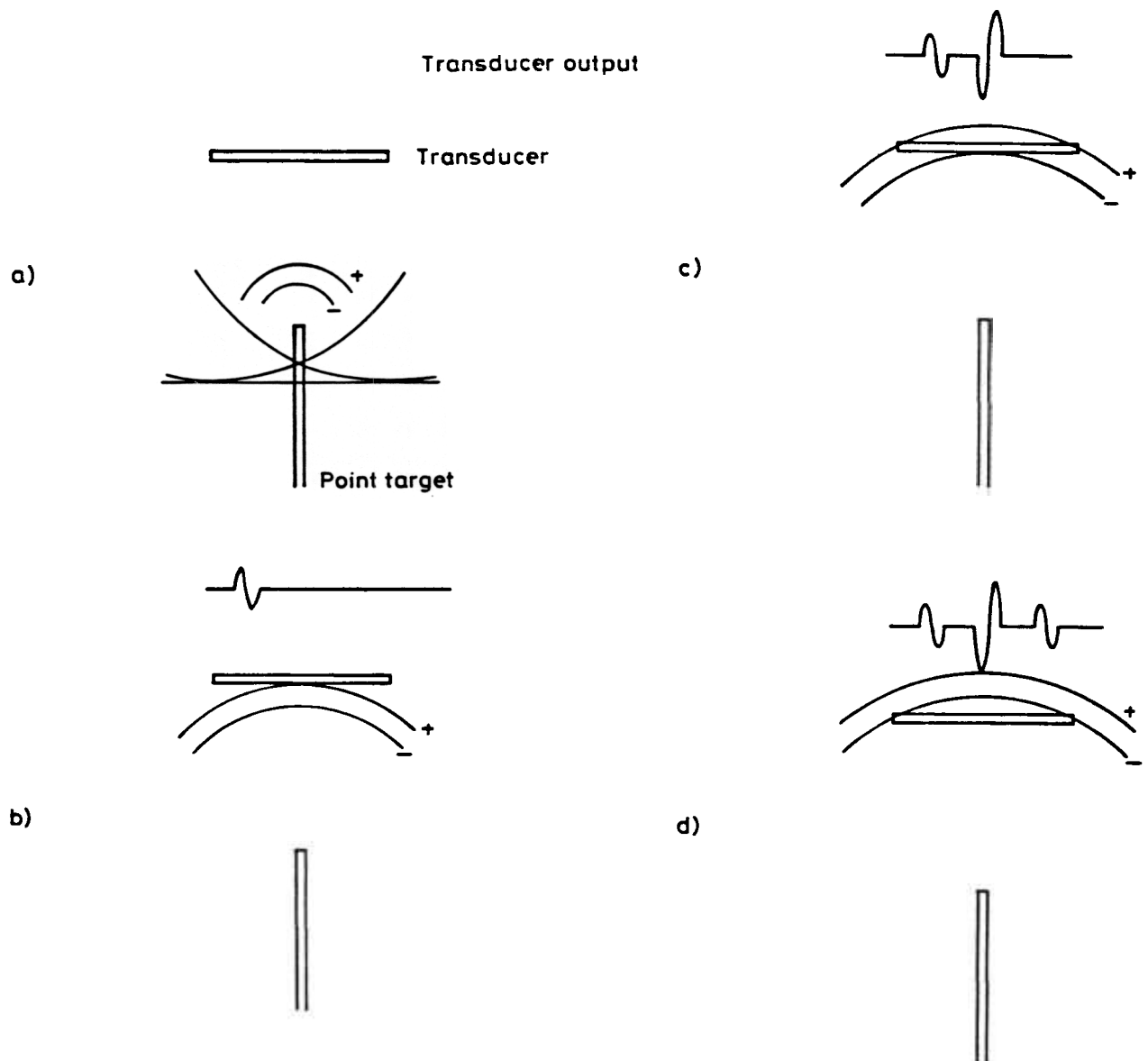


Figure E.1: Schematic representation of the pulse-echo response of a transducer to the reflection from a true point target placed on transducer acoustic axis. The sequence a) through to d) illustrates the propagation of the spherical wave from the point target as it sweeps across the transducer face along with the resultant transducer output. The waveform corresponding to d) represents the idealized pulse-echo response of the transducer to a point target.

This second component arrives slightly later in time due to the greater propagation distance. The two components are 180° out of phase and this is represented in Figure E.1 by different

polarities. The various contributions to the transducer output response result from these two components sweeping across its surface. Principally, three temporal components are may be identified:

the direct transmission, direct reception pulse arrives first (plane-plane component);

the edge-direct and direct-edge pulses arrive simultaneously, giving a pulse of double amplitude which is in anti-phase to the first arrival;

- finally a positive (in phase) edge-edge pulse is produced.

The resultant transducer output voltage may be seen in (d) of Figure E.1. The time-delay between the first two pulses arises due to the propagation time differences between the edge-wave and plane-wave components to the point target. Note that with the point target placed at the last-axial maximum (Y_0^+), these two components will be 180° out of phase and the four pulses given in Figure E.1 will coalesce. The idealized response of a transducer generating a single cycle of ultrasound and operating in pulse-echo mode to such a point target will therefore be a pulse containing four half-cycles of relative amplitudes 1:3:3:1. This response should be borne in mind when the behaviour of transducers to small ball target and disc reflectors is considered in Section 6.5.

E.3 THE RESPONSE OF A TRANSDUCER TO A SMALL BALL TARGET

It is important to understand the way in which a small ball target responds to a transducer field and this will be dealt with within this Section. Figure E.2 gives a schematic representation of a small ball target of radius b aligned on the acoustic axis at a distance z from a transducer of radius a . It is possible to understand the behaviour of the small ball target in terms of some quite simple geometrical arguments concerning waves originating from the transducer surface. Ultrasound on the transducer acoustic axis will be normally reflected backwards to the transducer. For increasing distances off axis, the ultrasound impinging on the ball will be reflected away from the transducer due to the curvature of the ball target. Indeed it is possible to identify an off-axis position (Δl_m) where the returning reflection from the small ball will just start to miss the transducer. This point is taken as defining the active area of the ball target. Through elementary geometry, it is possible to derive a value for Δl_m as

$$\Delta l_m = \frac{a_t}{1 + \frac{2z}{b}}$$

where it can be seen that as $z \rightarrow \infty$, $\Delta l_m \rightarrow 0$, as expected. The aim within the Part 2: Calibration Procedure is to determine the beam properties at the last-axial maximum (Y_0^+) and it is instructive to evaluate the value Δl_m for typical measurement situations. For a 5 MHz transducer of radius 5 mm positioned at Y_0^+ (equal to 84.3 mm), taking a small ball radius of 3 mm, gives a derived value for Δl_m of 0.09 mm (an effective diameter of 0.18 mm). At first sight this is perhaps surprisingly small; even increasing the ball target radius to 5 mm still only yields a Δl_m of 0.14 mm. These values should be noted in comparison to the predicted -3 dB beamwidth, which for this case is 2.55 mm. However, it should be noted that at smaller values of z , used, for example, used in the determination of the pulse-echo axial response of the transducer, greater values of Δl_m are produced. In the above example, taking $z = 15$ mm for the 3 mm radius ball target yields Δl_m equal to 0.45 mm so that the transducer response will be spatially-averaged over a diameter approaching 1 mm. This may in part give rise to the

relatively complex interaction observed close to the transducer face using a ball target identified in Section 6.5.

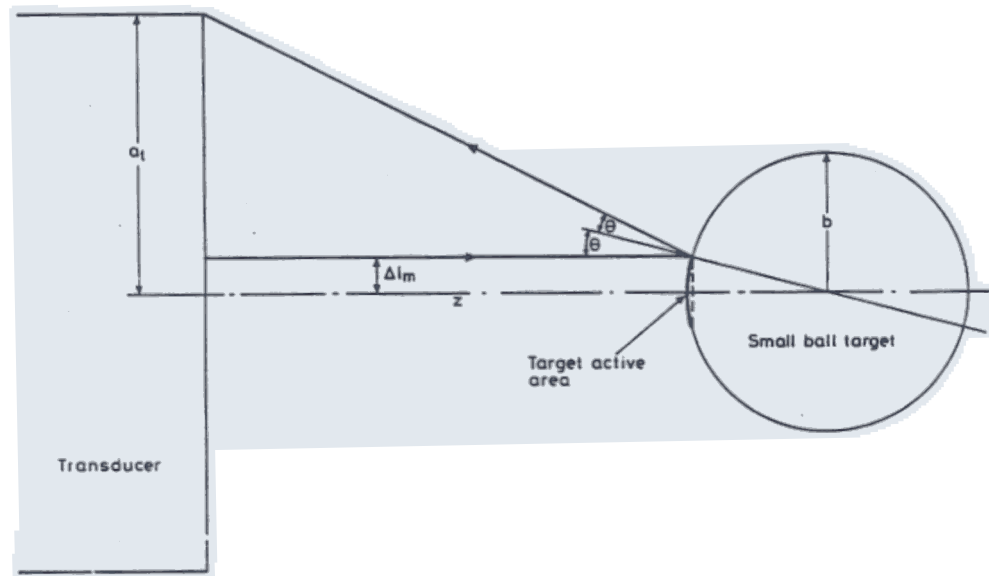


Figure E.2: Schematic diagram illustrating the extent of the active surface of a small ball target in a plane piston transducer field. For excursions away from the acoustic axis greater than l_m the returning normal reflection denoted by the path indicated will miss the transducer

In the ensuing assessment of spatial-averaging effects for small ball targets, it is assumed that for the unfocused transducer situation, the ball target behaves as an equivalent flat disc reflector of diameter $2\Delta l_m$. This is clearly an approximation as it ignores any axial variation in pressure field over the curvature of the scatterer, but it is considered to be a reasonable starting point.

E.4 AN ASSESSMENT OF SPATIAL-AVERAGING EFFECTS

Figure E.3 provides a general schematic representation of the measurement configuration of interest, illustrating a flat disc reflector of radius b , positioned off axis at a distance z from an unfocused transducer of radius a_t . In order to estimate the effect of spatial-averaging, a computer programme was written which enabled the pressure generated by a plane-piston transducer to be integrated over the surface of a disc positioned at or beyond the last axial maximum. The variation of pressure in the acoustic field is assumed to be given by the simple Bessel function outlined Appendix C. By repeating calculations at various positions perpendicular to the beam-alignment axis a beam plot could be simulated and beamwidths derived.

The situations involving hydrophones and pulse-echo small targets are clearly very different and the two were modelled in the following ways:-

for hydrophones, the hydrophone of radius b was scanned through the field, the acoustic pressure of the transmitted pressure field ($p_t(r)$), averaged over the aperture of the hydrophone being calculated at each position;

for pulse-echo targets, the response of the transducer is a convolution of the transmit properties of the transducer, the scattering response of the target and the response of the transducer in receive mode. Consequently, the computation was divided into two distinct parts. The average pressure of the transmitted pressure field over the disc target was firstly calculated. Second, the disc target was itself treated as a piston transducer, the integrated receive response of the transducer (radius a) being calculated. The overall response was taken as the product of these two components.

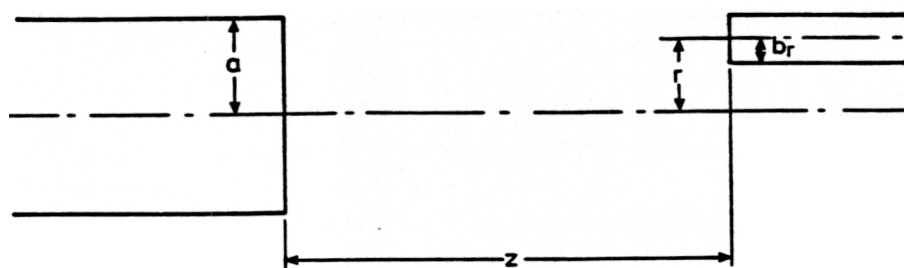


Figure E.3: Schematic diagram illustrating the configuration used for spatial-averaging calculations, showing the disc target of radius b_r placed in the field of a piston transducer of radius a_t and positioned at r , where r is the perpendicular distance from the transducer beam-alignment axis

E.4.1 Specification of hydrophone and pulse-echo target dimensions.

Each of the three specific measurement configurations considered will be dealt with in turn.

E.4.1.1 Hydrophones

Calculations were performed using various combinations of frequency and transducer diameter with the hydrophone in all cases positioned at the last axial maximum, Y_{0+} . The results are summarized in Figure E.4, where the ratio of the hydrophone diameter to the true beamwidth is presented against the measured -3 dB beamwidth normalized to the 'true' small (point) receiver value. The increase in measured beamwidth with increasing hydrophone size is clearly seen. For the error to be less than 2%, the ratio of the hydrophone diameter to the true beamwidth needs to be less than 1.16. If we take the case of an idealized plane-piston field, from Appendix C, the -3 dB beamwidth at the last axial maximum is given by:

$$\text{-3 dB beamwidth} = 0.5136 \times a_t$$

this, in combination with the requirement for the ratio of the hydrophone size to the true beamwidth, corresponds to the criterion for plane-piston fields such that

$$\text{hydrophone diameter} < 0.6 \times a_{\text{r}}$$

As the diameter of most C-scan transducers is typically 10 mm, this means that hydrophones smaller in diameter than 3 mm are sufficient to ensure that the effect of spatial-averaging on the measured beamwidth determined at Y_0 is negligible, a requirement which is easily realisable.

It should be noted that strictly the treatment outlined above is suitable only for plane-piston transducers. For those exhibiting focusing, beamwidths depend on the focal distance (Y_F) of the transducer and the ka value of the transducer, and tabulation of -3 dB beamwidths for various combinations of these two quantities can be found in Appendix C. From Table C.1 it can be seen that a hydrophone of diameter 1 mm will be suitable for most applications, provided that the -3 dB beamwidth is ≥ 0.83 mm. This is a satisfactory requirement for most C-scan transducers except for strongly focused devices of high ka for which $Y_F < 25$ mm.

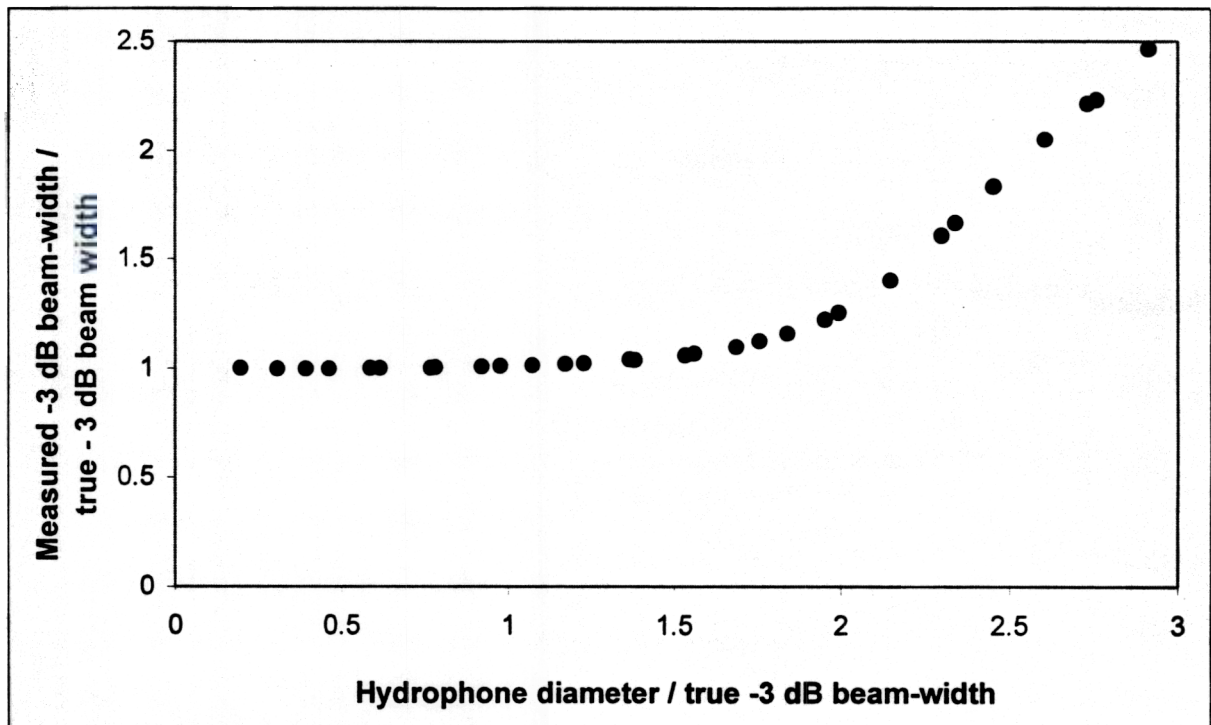


Figure E.4: Effect of spatial-averaging over the active element of the hydrophone on the measured -3 dB beamwidth. The ratio of the measured to true -3 dB beamwidth is presented against the ratio of the hydrophone diameter to the true -3 dB beamwidth

E.4.1.2 Pulse-echo measurements using disc reflectors

A series of calculations was undertaken using the example of a typical C-scan transducer: a 5 MHz transducer of diameter 10 mm with the small disc scatterer (flat-ended rod) positioned at the last axial maximum (taken as $84.3 \text{ mm} \equiv a^2/\lambda$). Figure E5 shows the results of the calculations with the measured -6 dB pulse-echo beamwidth normalised to the point target value plotted as a function of the disc reflector diameter, again normalised to the true -6 dB pulse-echo beamwidth. Figure E6 gives the information in a slightly different form, as the

error in the measured beamwidth plotted as function of the ratio of the disc diameter to the measured -6 dB pulse-echo beamwidth which is determined directly from the measurement.

Clearly from these two figures, in order that the error in the beamwidth measurements be maintained below 2%, the ratio of the beamwidth to the disc diameter must be greater than 1.9. For the idealized plane-piston case this corresponds to:-

$$\text{disc diameter} < 0.27 a_t$$

so that for a transducer diameter of 10 mm, a rod of diameter smaller than 1.3 mm should ideally be used. The greater effect of spatial-averaging relative to Figure E4 (hydrophone) in the case of small disc targets is clearly seen.

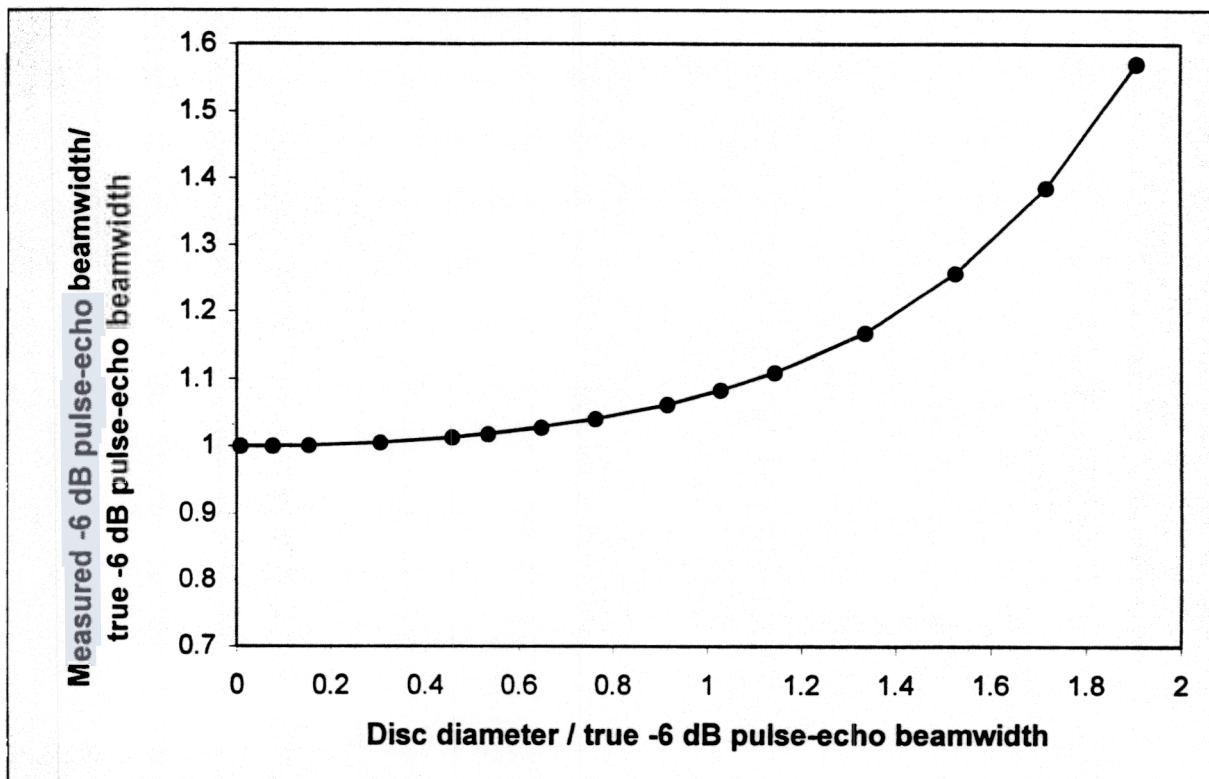


Figure E.5: Effect of spatial-averaging on the measured -6 dB pulse-echo beamwidth derived using a disc reflector. The ratio of the measured to true -6 dB beamwidth to the true -6 dB pulse-echo beamwidth is presented against the ratio of the disc diameter to the true -6 dB beamwidth

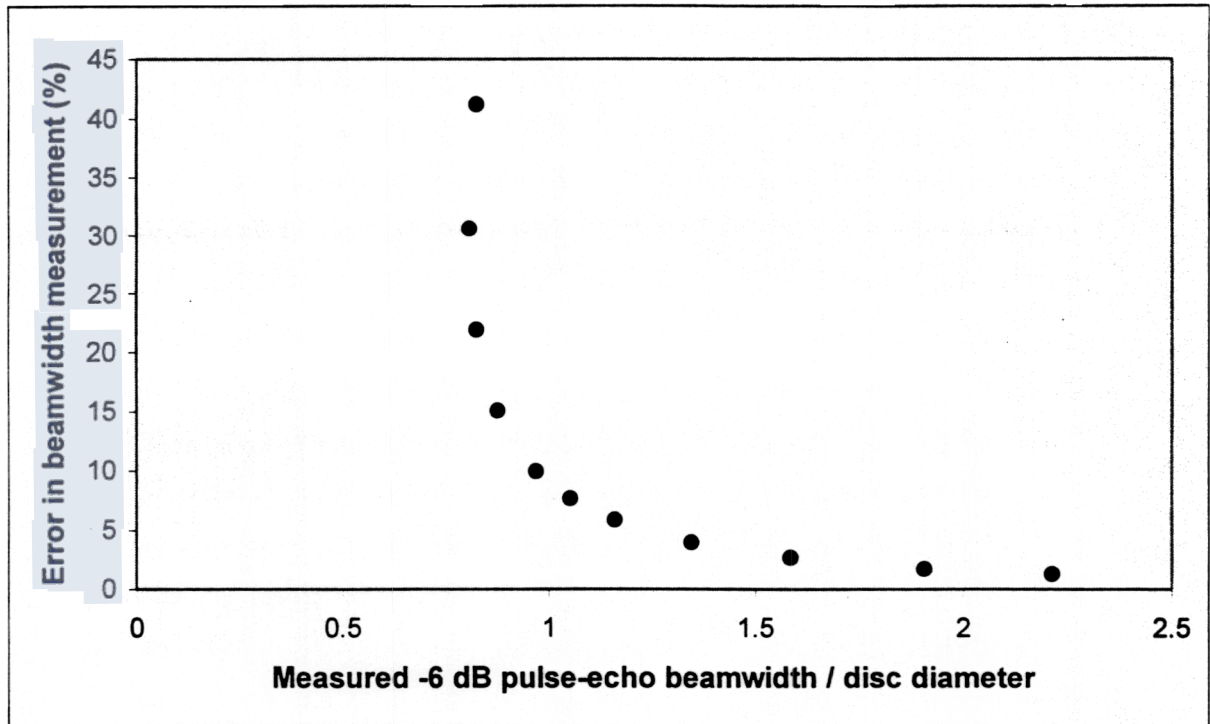


Figure E.6: Effect of spatial-averaging on the measured -6 dB pulse-echo beamwidth derived using a disc reflector. The data is identical to that presented in Figure E.5, but has been presented in a different form. In this case, the percentage error in the beamwidth measurement is presented against the ratio of the measured -6 dB pulse-echo beamwidth to the disc diameter

E.4.1.3 Pulse-echo measurements using small ball targets

As has been pointed out in Section E.2 of this Appendix, the region of the small ball target which actually responds to ultrasound from the transducer is relatively small and one would intuitively expect spatial-averaging effects to be of lesser importance in this case. The effective disc diameter was derived previously as $2\Delta l_m$ and therefore using this, and the criterion derived earlier for the disc reflector case that the ratio of the -6 dB pulse-echo beamwidth to the disc diameter must be greater than 1.9, leads to the requirement that

$$b < 0.31 N_{\text{nom}} \text{ (or } Y_{0+}\text{)}.$$

At first sight this stipulation is surprising loose; for many C-scan unfocused transducers values of Y_{0+} are typically 40 mm to 60 mm and the above expression implies that ball targets of radii in the range 12 mm to 18 mm may be used in this situation. This underlines the fact that ball targets used at the positions of Y_{0+} and beyond are remarkably tolerant of spatial-averaging effects. In the Part 2: Calibration Procedure, the criterion used for measurements on unfocused fields is tighter than that given above due to concerns regarding the response for distances $z < \frac{1}{2} Y_{0+}$, so that $b < 0.1 Y_{0+}$.

Note that this analysis again may not be appropriate for focused transducers due to the complex response of a focused to scattering from the ball target.

E.5 REFERENCES

- E1 WEIGHT, J.P and HAYMAN, J. "Observations of the propagation of very short pulses and their reflection by small targets", *J. Acoust. Soc. Am.*, 1978, 62, 396-404.

APPENDIX F: PERSPEX ACOUSTIC PROPERTY MEASUREMENT COMPILATION

F.1 BACKGROUND

The work undertaken by DERA on the absolute measurement of attenuation, relied on the establishment of the true bulk attenuation. Section 9 describes reference measurements made on a Perspex step-wedge. However, it is also instructive to look at the range of values of attenuation documented in the technical literature. This is done in Figure F1, where values derived from 5 references are presented alongside measurements made at NPL on its own specimens of Perspex. These measurements were undertaken using two thicknesses of Perspex (6 mm and 30 mm) using a through-transmission-substitution technique as described. A 30 mm diameter hydrophone was used for these measurements. Figure F1 illustrates the range of values produced by the various studies, indicating the crucial importance of a reliable reference value against which measurements of C-scan attenuation can be reliably checked. These reference measurements should ideally be performed on the same specimen to be used for absolute attenuation measurement as variations may exist between materials sourced from different suppliers.

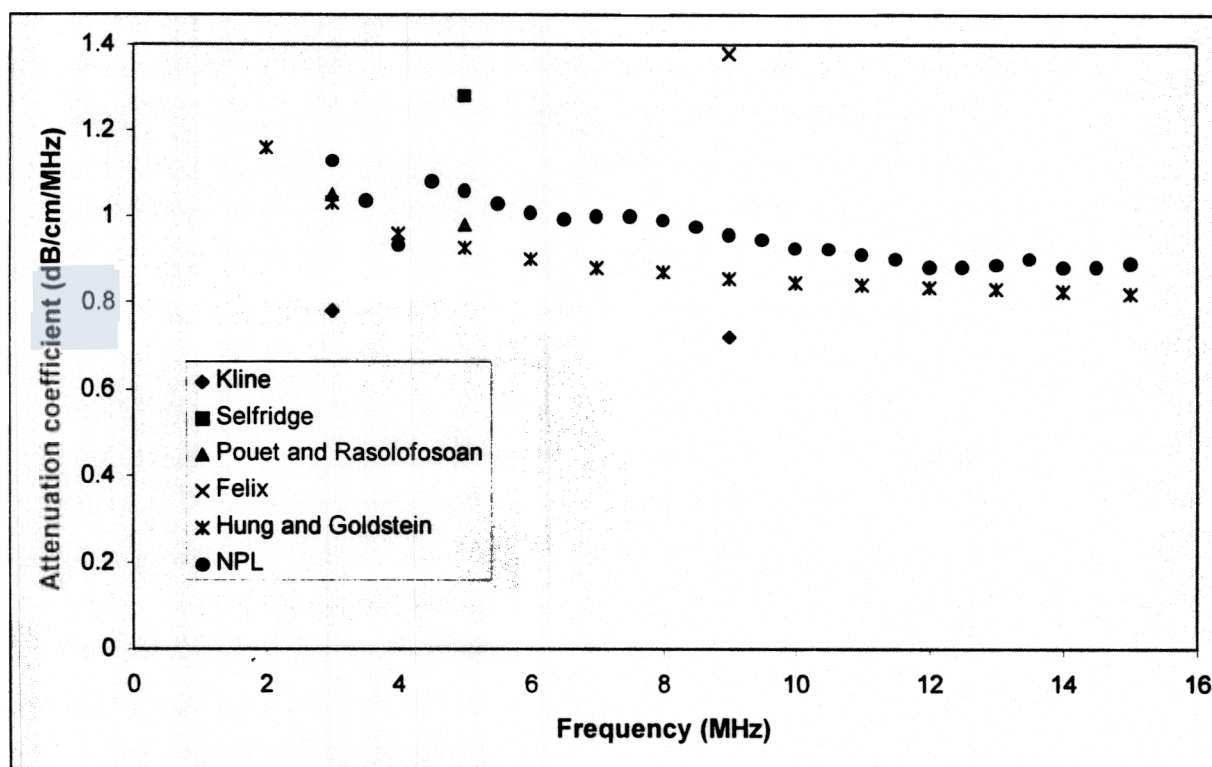


Figure F.1: Compilation of attenuation coefficient data from 5 authors, plus NPL data

F.2 REFERENCES

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- F2 FELIX, M.P. "Attenuation and dispersion characteristics of various plastics in the frequency range 1 to 10 MHz"; *J. Composite Materials*, 1974, 8, 275.

- F3 POUET, B.F., RASOLOFOSOAN, N. J. P. "Measurement of broadband intrinsic ultrasonic attenuation and dispersion in solids with laser techniques", *J. Acoust. Soc. Am.*, 1993, **93**, 1286-1292.

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- F5 KLINE, R.A. "Measurement of attenuation and dispersion using an ultrasonic spectroscopy technique", *J. Acoust. Soc. Am.*, 1984, **76** (2), 498-504.