

REPORT

Aperture-based measurement of the effective radiating area of physiotherapy treatment heads: a new rapid system and detailed performance evaluation

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ABSTRACT

This report comprises both theoretical and experimental studies to develop a new, rapid implementation of the aperture technique for determining the effective radiating area (A_{ER}) of physiotherapy ultrasound treatment heads. The performance of the technique when using radiation force balances with both absorbing and reflecting targets is compared, alongside reference measurements performed to IEC 61689 criteria. The design and realisation of a new integrated system for determining power and A_{ER} is described, and tests and validation measurements have shown good agreement with IEC 61689 data, and with the original implementation of the aperture technique. Finite-element modelling has also been used to predict the aperture-derived A_{ER} values of the reference transducers used, and to derive correction factors for the effect of acoustic diffraction from the aperture.

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ISSN 1369-6785

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1 BACKGROUND

Physiotherapy ultrasound remains one of the most commonly used clinical modalities, with an estimated 10,000 units in operation within the United Kingdom and several million treatments administered annually (1). The technique is typically used to bring pain relief to soft tissue injuries, but has also found application in the accelerated healing of scar tissue. Although devices operating in the range 40 kHz to 50 kHz have appeared within the last few years, the traditional frequency of application typically lies within the range 0.75 MHz to 3 MHz. The treatment heads used to deliver the ultrasonic energy are made up of an air-backed piezoelectric crystal, bonded to a metallic front face which is coupled to the body of the patient using transmission gel. The electrical drive to the treatment head may be driven either continuously, or in bursts, to vary the way that the energy is applied to the tissue. Spatial-average intensities between 0.2 W cm^{-2} and 2.0 W cm^{-2} are normally applied.

Although the exact mechanism of therapeutic benefit remains uncertain, the ability of such equipment to cause harm to patients was brought into sharp relief by the issuing of a Safety Action Notice (SAN) (2). Within this Notice, it was documented that two systems delivered excessive acoustic output resulting in injuries to two patients. It recommended that such equipment should be the subject of regular calibration tests to ensure performance is within the tolerances of international specification standards. Some of the key relevant quantities will now be described in detail.

1.1 MEASUREMENT OF OUTPUT POWER

Due to the availability of suitable commercial measuring equipment, measurements of certain characteristics of treatment heads has now become reasonably straightforward. Total ultrasonic output power, for example, can be measured using a radiation force balance (3). At MHz frequencies, the majority of treatment heads used to deliver physiotherapy produce reasonably collimated beams. Targets placed within the acoustic beam experience a force whose measurement is readily related to the power within the beam (4). Good quality radiation force or power balances, such as the ElectroMedical Supplies or Ohmic Instruments balances, are now commercially available. However, their use does require a degree of skill and training, and, for this and other reasons such as cost and the time taken to set the systems up, they are not really appropriate for use at the user level. The availability of these radiation force balances, means that measurements of output power can be made which are ultimately traceable to national standards of measurement.

1.2 BEAM PROPERTY CHARACTERISTICS: A_{ER} AND R_{BN}

Measurements of the beam properties of physiotherapy treatment heads are more complicated to undertake. Due to their highly resonant behaviour, the motion of the front face of the treatment head is far from piston-like and, being dependent on the ratio of the diameter of the piezoelectric crystal to the wavelength, radial excitations of the crystal can additionally be generated. The resultant pressure distribution within the ultrasonic field is highly complex and cannot easily be predicted; it therefore has to be measured directly (5, 6). The reference technique for carrying this out, IEC 61689, is to use miniature hydrophones, of typical active element diameter 0.6 mm or 1 mm, to sample the pressure distribution in the field (7). The hydrophone is moved in a grid or raster pattern, ensuring that the whole of the acoustic field is sampled. Measurements require a relatively sophisticated system, capable of scanning the hydrophone and of acquiring and analysing the data. This degree of capability is likely to be in place only at manufacturer level or specialist test houses.

The measurements embodied with IEC 61689 are used to derive two key parameters describing the distribution of pressure or intensity within the acoustic beam. The first of these is the effective radiating area (A_{ER}). The A_{ER} is defined as the area at, or close to, the face of the treatment head, through which the majority of the ultrasonic power passes. The A_{ER} is an important safety parameter, as it is used to evaluate the Effective Intensity, I_{eff} , given by:

$$I_{eff} = \frac{W}{A_{ER}}$$

where W is the ultrasonic power generated by the treatment head. In cases where this is the *rated output power*, or the maximum power capable of being delivered by the machine, it can be viewed as the maximum spatially-averaged intensity which the physiotherapy device is capable of delivering. IEC 61689 limits this to 3 W cm^{-2} , a criterion that comes from the World Health Organisation (8) and arises because adverse biological effects may occur at higher intensities (9). As the beneficial effects arising from physiotherapy ultrasound occur using exposure levels less than 3 W cm^{-2} , there is no justification for employing higher levels.

It should be appreciated that I_{eff} represents an average intensity over the A_{ER} , and that within the acoustic field, values of local intensity may significantly exceed this value. The beam nonuniformity ratio (R_{BN}), which is defined as:

$$R_{BN} = \frac{I_{spta}}{I_{eff}}$$

characterises the degree of this, where I_{spta} is the spatial-peak temporal-average intensity within the acoustic field. An R_{BN} of 4, for example, is generated by an ideal plane-piston transducer, implying that the I_{spta} will have a maximum value of 12 W cm^{-2} for a treatment head meeting the I_{eff} safety criterion. IEC 61689 sets an upper limit of 8 on treatment heads. High R_{BN} treatment heads have often been termed ‘hot-spot’ transducers.

1.3 A SIMPLE, LOW COST METHOD FOR MEASURING A_{ER}

From the above analysis, it can be seen that there existed a specific need for a measurement technique for measuring A_{ER} which could be readily applied at the hospital level, and which circumvented the need for a sophisticated hydrophone beam-plotting system. Ideally, such a technique should use a radiation force balance, as such devices are routinely used for the assessment of physiotherapy ultrasound equipment. To meet this need, NPL developed the aperture method of determining A_{ER} based on the use of a series of absorbing apertures. A description of the technique in combination with the validation measurements carried out on a range of treatment heads has been described previously in detail (10). Only an overview of the key features will be given here.

The apertures are fabricated from a special polyurethane based acoustic absorber (11), which combines a high transmission loss ($28 \text{ dB cm}^{-1} \text{ MHz}^{-1}$), which is frequency dependent, with a low front face reflection (reflection loss is less than -40 dB over the frequencies of interest). Within the flat layers of this material, precision apertures of various diameter are cut such that when the apertures are placed between the treatment head and the target of a radiation

force balance as shown in Figure 1.1, the ultrasonic power over the aperture is effectively sampled.

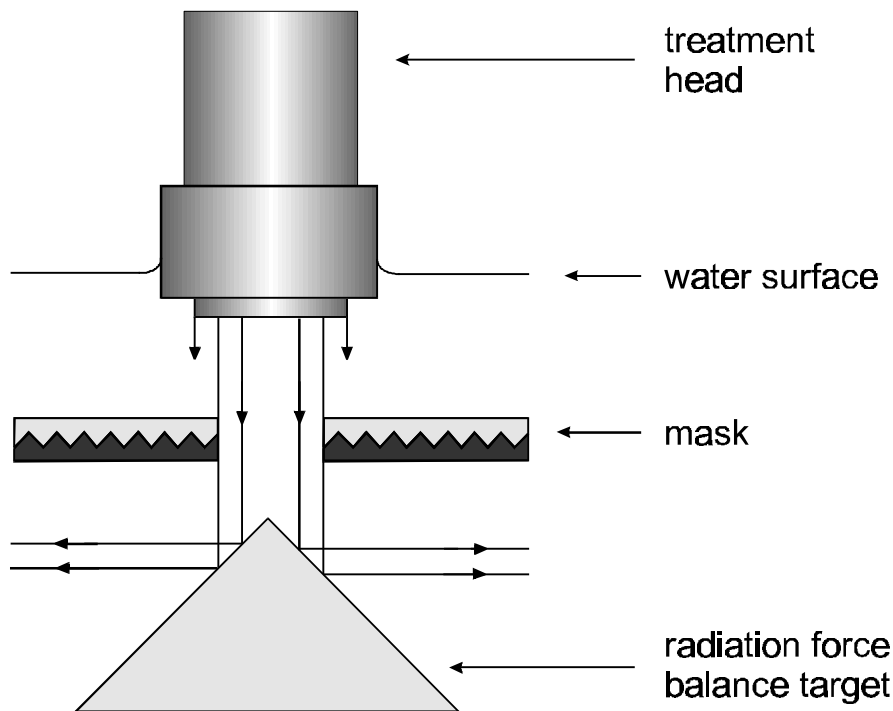


Figure 1.1: Schematic representation of aperture technique

By completing measurements of power using various sized apertures and analysing the results using a standard protocol (10), the value of the A_{ER} for the treatment head may be derived. The original publication described the validation of the technique through a comparison with IEC 61689 hydrophone derived values for 17 treatment heads. Levels of agreement between the two methods were typically $\pm 11\%$.

It is worthy of note that the aperture method is similar to the technique described in IEC 60150 (12), where a series of conical stainless baffles of various apertures are used to gradually reduce the radiation area of the treatment. The A_{ER} is taken as the area of the steel baffle (multiplied by a factor 1.1) which transmitted 90% of the power. This method was found to be difficult to implement and was of poor reproducibility (13) and thus was eventually replaced by IEC 61689.

Although in concept the aperture and conical baffle methods are similar, it is not immediately clear why the NPL aperture method works so much better. There may be a number of reasons for this but the use of the special absorbing materials resulting in less perturbation to the acoustic field and the improved method of analysis, are probably the key ones.

1.4 THE NEED FOR FURTHER WORK

Although the original work carried out on the aperture method was extremely encouraging, several aspects of their use still had to be investigated and refined. These were:

- the implementation of the aperture method described in (10) involved removing the treatment head under test, positioning the aperture over the radiation force balance target and then re-aligning the treatment head. This was necessarily time-consuming and there existed a need to design, build and validate a more rapid system which could potentially be applied within industry;
- the original aperture study involved an implementation using a style of radiation force balance similar to that produced by ElectroMedical Supplies which utilises a conical reflecting target. It is now well documented that, for certain types of treatment head, reflecting target radiation force balances can underestimate the power (14). This is principally true for low ka transducers, where some of the beam misses the target, leading to an under-reading of the power. This was particularly likely to be an issue when using the apertures as a result of diffraction from the aperture. There was therefore a need to develop a system based on an absorbing target;
- there was a need to explore the relationship between A_{ER} values derived using radiation force balances based on reflecting and absorbing targets;
- the measurement of the A_{ER} for small ka treatment heads is known to be problematic (7), and so some investigation was needed to examine the effects of diffraction. It was felt that this would best be carried out by producing a theoretical model of the apertured transducers, and using this to investigate the possibility of deriving a correction for the values for A_{ER} produced by the aperture method. Recently, a finite element (FE) modelling facility has been set up at NPL, and this would be an appropriate tool for setting up such a model;
- an assessment of the overall measurement uncertainty of the aperture method needed to be derived.

2 NUMERICAL MODELLING

The aim of the work described in this section is to simulate measurements of radiation force when an apertured transducer is used in conjunction with an absorbing target, as depicted schematically in Figure 2.1. This is done in order to provide key data in establishing guidelines for the implementation of the aperture method to measure small ka treatment heads.

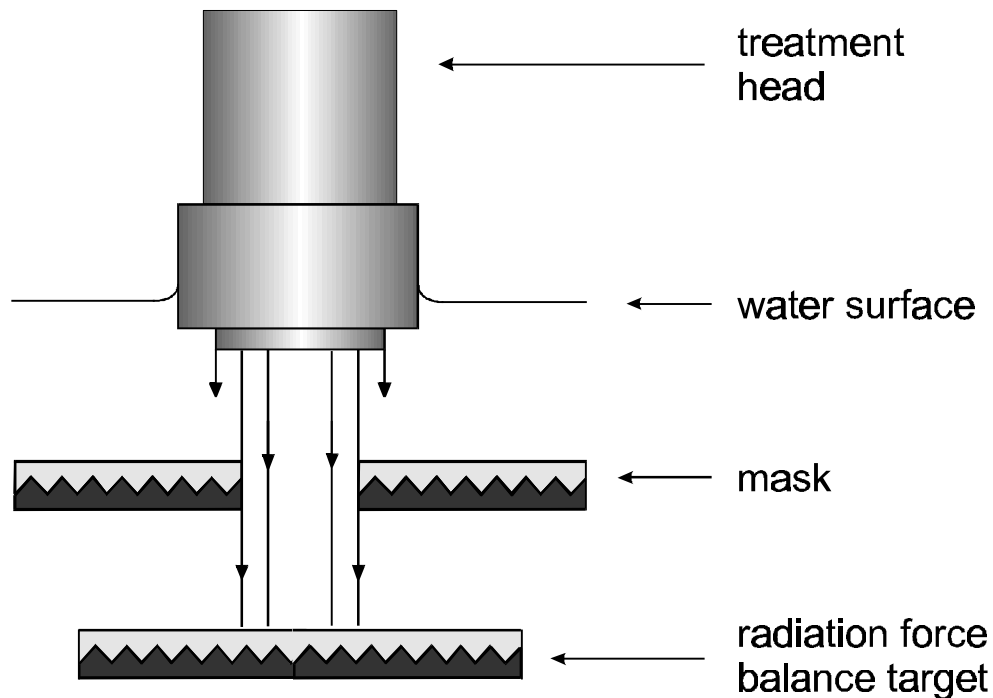


Figure 2.1: Schematic representation of aperture technique, absorbing target

Considering the current problem, there exists an expression of the solution to the problem in the un-apertured case, when a circular plane piston is rigidly vibrating in an infinite baffle and radiating into a semi-infinite fluid. An analytical expression which is capable of accounting for the presence of the aperture in the medium, together with its dynamic properties when subjected to an incident sound field, is unlikely to exist. A numerical solution to the problem must therefore be sought. The Finite Element (FE) method was used during this study.

2.1 BACKGROUND TO PAFEC

NPL's Centre for Mechanical and Acoustical Metrology employs the PAFEC (Program for Automatic Finite Element Computation) vibroacoustics software package to apply finite element and boundary element modelling techniques to the solution of acoustic transducer design and acoustic field propagation problems. PAFEC is marketed by SER Systems Ltd and their mathematicians have worked with NPL both to extend the functionality of the PAFEC software and to provide NPL with bespoke software to tackle specific modelling problems.

The computing platform on which the generated code is used is a Sun Ultra 2 workstation running the Sun Solaris 2.6 operating system, with levels 8.5 and 8.6 of the PAFEC vibroacoustics finite element software package installed. This package allows problems

involving fluid-structure interaction to be modelled without having to deal with each section of the problem individually.

2.2 REVIEW OF THEORY OF ACOUSTIC RADIATION FORCE AND RADIATION POWER ON AN ABSORBING TARGET

2.2.1 Radiation force

N.B.: vectorial quantities are depicted in bold.

Consider a homogeneous, non-absorbing, sound-propagating fluid characterised by a sound speed c and a mass density $\tilde{n}$. Assume that an arbitrary sound field with acoustic pressure $p(\mathbf{r}, t)$ and particle velocity $\mathbf{u}(\mathbf{r}, t)$, in Eulerian coordinates, exists in the medium. The particle velocity vector $\mathbf{u}$ has the Cartesian components u_1 , u_2 and u_3 . An expression of the force exerted by a sound field on a target may be obtained by considering the acoustic radiation stress tensor given by (15):

$$S_{ij} = -\overline{p}d_{ij} - ru_iu_j \quad (1)$$

where

- $\overline{d_{ij}}$ is the Kronecker delta
- $\overline{p}$ is the time-averaged acoustic pressure
- i and j assume values of 1, 2 and 3.

The acoustic radiation force vector $\mathbf{F}$ on the target is given by the vectorial surface integral of the tensor S_{ij} over a closed surface which contains the target in its interior (15, 16):

$$\mathbf{F} = -\oint \mathbf{S} \cdot d\mathbf{A} \quad (2)$$

where the vectorial surface element $d\mathbf{A}$ is an infinitesimal vector normal to the surface of integration.

In the case of linear propagation and sinusoidal excitation, the quantity $\overline{p}$ in equation (1) goes to zero. It is assumed that the edge effects at the target may be neglected. The problem is assumed to be axisymmetric and the target is therefore circular and has the same axis of symmetry as the source of sound which is assumed to be a circular piston transducer. Let x be the axis of symmetry and R the radial axis. In practice, the force-measuring device is aligned with the x -axis. Hence, it is only necessary to consider F_x , the axial component of the radiation force vector $\mathbf{F}$. From now on, F_x will be referred to simply as F . Following these considerations, equation (2) leads to:

$$F = -\iint S_{11} dA = 2p \int_0^b T_x(x, R) R dR = 2p \int_0^b r |\hat{u}_x(x, R)|^2 R dR \quad (3)$$

where

- b is the target radius and where the hat (^) denotes the complex amplitude so that, for example, $p(\mathbf{r}, t) = \hat{p}(\mathbf{r})e^{j\omega t}$
- $T_x(x, R)$ is the kinetic energy density due to the axial particle velocity.

It can be seen that, in the general case, the radiation force on an absorbing target may be obtained by knowledge of the normal particle velocity distribution on the target.

2.2.2 Acoustic power on the target

Another quantity of interest is the acoustic power resulting from the normal acoustic intensity on the target. This may be obtained from integrating this latter quantity over the surface of the target:

$$P = 2p \int_0^b I_x(x, R) R dR \quad (4)$$

where I_x is the normal component of the acoustic intensity vector $\mathbf{I}$.

I_x is given by (17):

$$I_x = \frac{1}{2} [\hat{p}(x, R)^* \hat{u}_x(x, R) + \hat{p}(x, R) \hat{u}_x(x, R)^*] = |\hat{p}(x, R)| |\hat{u}_x(x, R)| \cos(f_u - f_p) \quad (5)$$

where

- f_u and f_p are the phase terms of $\hat{u}(x, R)$ and $\hat{p}(x, R)$ respectively
- $*$ denotes the complex conjugate.

2.2.3 Un-apertured case

In the case where there is no aperture present, there exists an expression for the axial component of the acoustic radiation force on an absorbing target when a circular piston is rigidly vibrating in an infinite baffle and radiating into semi-infinite space.

The velocity potential Φ is defined so that (17):

$$\mathbf{u} = -\vec{\nabla} \Phi \quad (6)$$

where, in cylindrical coordinates (18):

$$\vec{\nabla} = \frac{\partial}{\partial x} \vec{x} + \frac{\partial}{\partial R} \vec{R} + \frac{1}{R} \frac{\partial}{\partial q} \vec{q} \quad (7)$$

In the axisymmetric case, equation (7) becomes simply:

$$\vec{\nabla} = \frac{\partial}{\partial x} \vec{x} + \frac{\partial}{\partial R} \vec{R} \quad (8)$$

The axial component of the particle velocity is therefore:

$$u_x = -\frac{\partial \Phi}{\partial x} \quad (9)$$

For a plane piston, the velocity potential is given by (15):

$$F(\mathbf{r}, t) = \frac{1}{2\delta} \hat{u}_n e^{j\omega t} \iint_{A_1} \frac{e^{-jk|\mathbf{r}-\mathbf{r}_1|}}{|\mathbf{r}-\mathbf{r}_1|} dA_1 \quad (10)$$

where

- A_1 is the piston surface area
- $\hat{u}_n$ is the maximum piston velocity
- $\mathbf{r}_1$ is the position vector of a point on the piston
- $\mathbf{r}$ is the position vector of a point in the sound field.

The acoustic pressure at any point defined by $\mathbf{r}$ in the field is given by (17):

$$p(r, t) = r \frac{\partial}{\partial t} \Phi(r, t) = j\omega r \Phi(r, t) \quad (11)$$

Hence, once the velocity potential Φ has been evaluated, the axial component of the acoustical radiation force and the acoustic power may be obtained at any point in the field using equations (3) and (4).

For comparison purposes, it is advantageous to rely on an expression which is entirely analytical. It may be shown that (15), in the configuration depicted in this section, the ratio of F_c/P is given by:

$$\frac{F_c}{P} = \frac{1 - J_0^2(ka) - J_1^2(ka)}{1 - \frac{J_1(2ka)}{ka}} \quad (12)$$

2.3 FE MODEL OF APERTURED TRANSDUCER CONFIGURATION

2.3.1 Pressure field produced by an apertured 1 MHz large transducer

2.3.1.1 Transducer modelling

In this study, the transducers under study are of the circular piston type. It is assumed that the problem is symmetric about the axis of symmetry of the transducer and only circular apertures are considered. The transducer is radiating into a semi-infinite homogeneous non-absorbing fluid, so that the only reflections that occur take place at the aperture. Consideration was given as to how the transducer should be modelled. At first, it was considered that the physiotherapy transducer model developed in (19) be used. However, given the difficulty in modelling a given transducer and reconciling the predicted acoustic field with measured fields, it was decided that this would perhaps not be the best approach, since the use of more than one FE transducer model would be required. An ideal rigidly-vibrating plane piston mounted in an infinite baffle was therefore used. Although it is well known that ultrasonic transducers do not move as a rigid body at their frequency of operation (20), this is considered as a first step towards the prediction of apertured acoustic fields.

For the piston model, three-noded thin axisymmetric shells of revolution were used. In an axisymmetric problem in PAFEC, it should be noted that the axis of symmetry is by default the x-axis. The circular piston has been mounted in the y-z plane at $x=0$. The piston is

assumed to be of steel and to have a diameter of 5 mm and a thickness of 0.1 mm. The material properties and thickness of these elements are however not really an issue since all degrees of freedom except for the x -direction translational degree of freedom in the piston are restrained. The piston moves as a rigid body with an assumed velocity of 0.01 m s^{-1} at a frequency of 1 MHz. Knowledge of the piston velocity is not crucial to the problem, since linearity is assumed. It is however relevant when comparing results in the un-apertured case when directly solving the double integral in equation (10).

2.3.1.2 Aperture modelling

The aperture was modelled using eight-noded isoparametric curvilinear quadrilateral elements for axisymmetric problems. When rotated about the x -axis, these effectively form a solid of revolution.

At the time of modelling, not all the material properties were available. It should first be noted that there are two types of material that constitute the aperture and these are bonded together in a way that is not straightforward to model. A full three-dimensional model would be required in this case. It is however known that a solid slab of the materials that form the aperture is designed to produce an on-axis insertion loss at 1 MHz of 30 dB (11). From knowledge of this, the slab may be approximated using one “equivalent” material. Also, it is known that both materials possess similar properties. The material density is known to be 1010 kg m^{-3} . Young’s Modulus may be deduced by assuming that the material has a normal-incidence pressure reflection coefficient of 0.01 and this was found to be $2.23 \times 10^9 \text{ Pa}$. Poisson’s ratio was assumed to be 0.4 and the damping ratio was obtained through trial and error to be 0.17 – this process involved varying the damping ratio of the modelled material until the overall transmission loss was equivalent to that found experimentally. A hysteretic damping model was used.

2.3.1.3 Propagating medium modelling

The fluid between the piston and the aperture was modelled using axisymmetric pressure-based fluid finite elements. These elements have eight nodes and one degree of freedom, which is pressure. The properties of the medium are those of water. The Bulk modulus K and the fluid density ρ are both functions of temperature. Investigating the properties of apertured sound fields as a function of temperature was however beyond the scope of this project and the chosen values for K and ρ were respectively $2.25 \times 10^9 \text{ Pa}$ and 1000 kg m^{-3} . This gives a sound speed of 1500 m s^{-1} . Fluid finite elements were used in the space between the piston and the aperture and within the aperture as well. The boundaries of the aperture that have the largest x and y coordinates (i.e. the lines $x=165 \text{ mm}$ and $y=22.5 \text{ mm}$) are where the boundary element has been placed. This enables a semi-infinite region of fluid to be modelled. The piston is backed by vacuum and symmetry of the boundary element is defined about the y -axis, hence effectively modelling an infinite baffle.

2.3.1.4 Pressure contour plots of apertured 1 MHz large transducer

Using the basic model that has been set up, it was of interest to visualise the effects of inserting apertures of various diameters in front of a rigidly vibrating piston mounted in an infinite baffle. The properties of the piston, aperture and propagating medium are reviewed below.

Piston properties:

- Radius: 12.5 mm
 - frequency $f=1$ MHz
 - piston velocity is 0.01 m s^{-1}
- (N.B. material properties are irrelevant due to rigid vibration)

Aperture properties

- aperture inner diameter: 0, 4, 6, 9, 12, 16, 19, 22, 24, 30 mm
- aperture outer diameter: 45 mm
- aperture thickness: 14 mm
- piston-aperture separation: 2.5 mm
- mass density: 1010 kg m^{-3}
- Young's modulus $E=2.23 \times 10^9 \text{ Pa}$
- Poisson's ratio: $\nu=0.4$
- Damping ratio (hysteretic damping): $d=0.17$

Propagating medium properties:

- mass density $\rho=1000 \text{ kg m}^{-3}$
- Bulk modulus $K=2.25 \times 10^9 \text{ Pa}$, hence giving $c=1500 \text{ m s}^{-1}$

The pressures are obtained at points along a rectangular grid in the boundary element. This is done in the post-processing phase. These pressures are evaluated 0.5 mm into the boundary element. The obtained pressure matrix is then transferred to MATLAB® and is displayed in the form of contour plots.

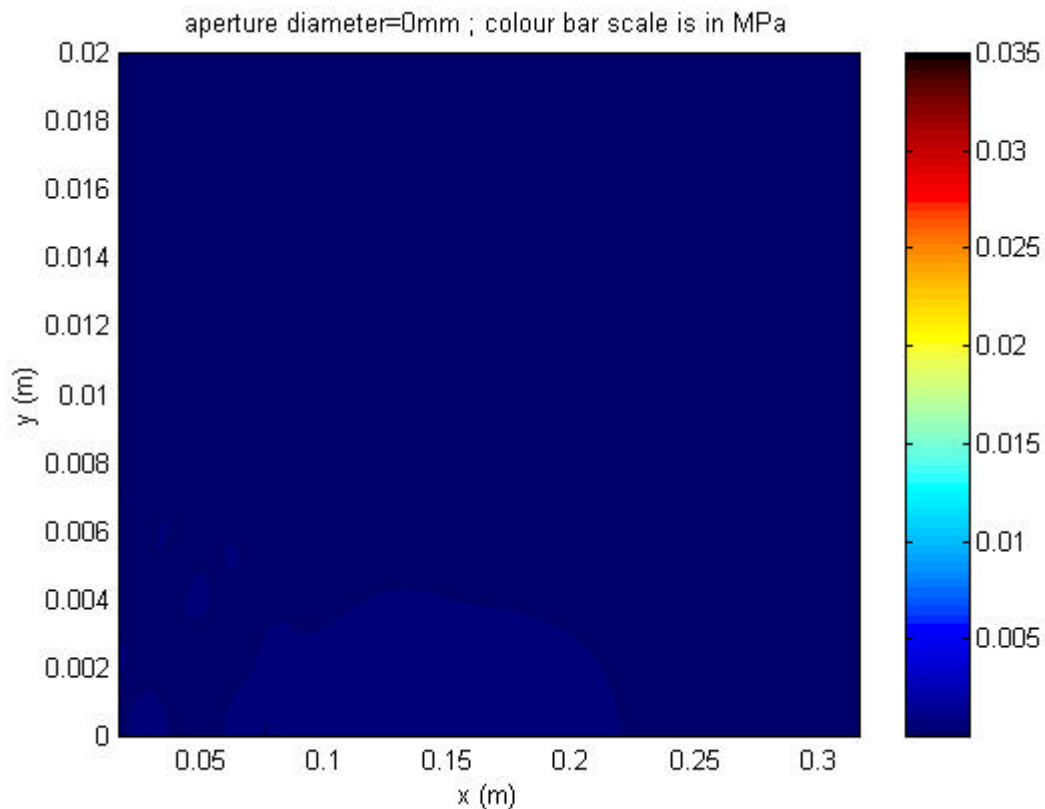


Figure 2.2: Contour plot of pressure field when a 0 mm aperture is used

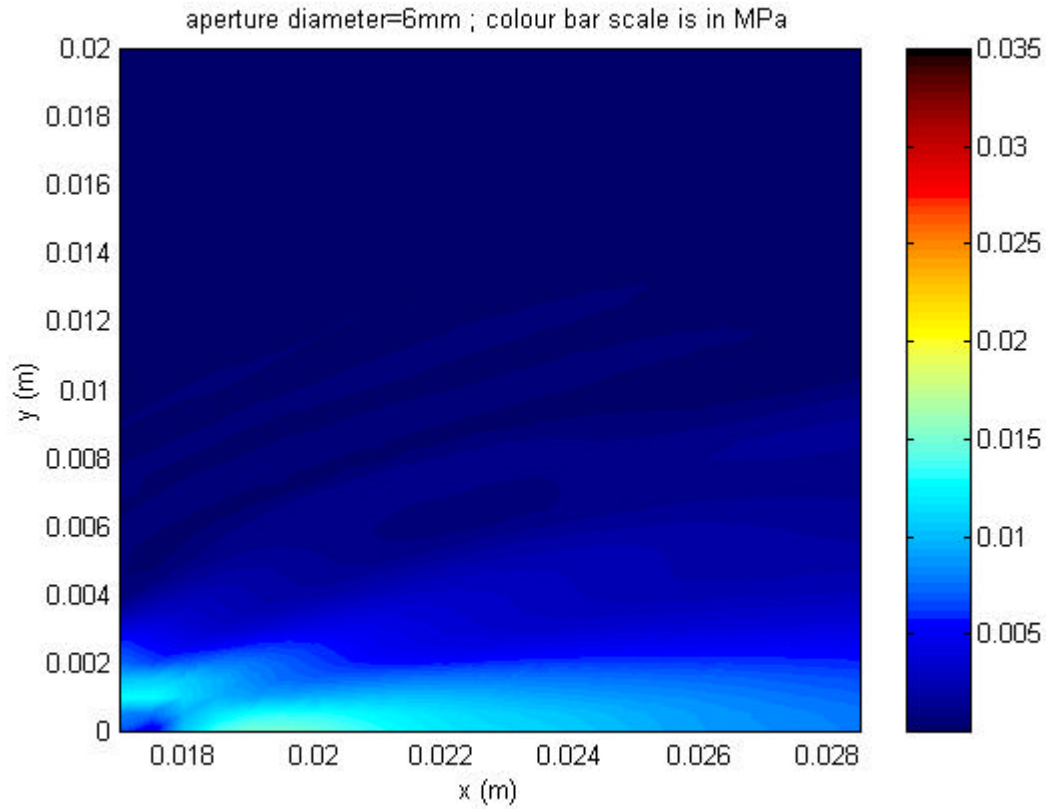


Figure 2.3: Contour plot of pressure field when a 6 mm aperture is used

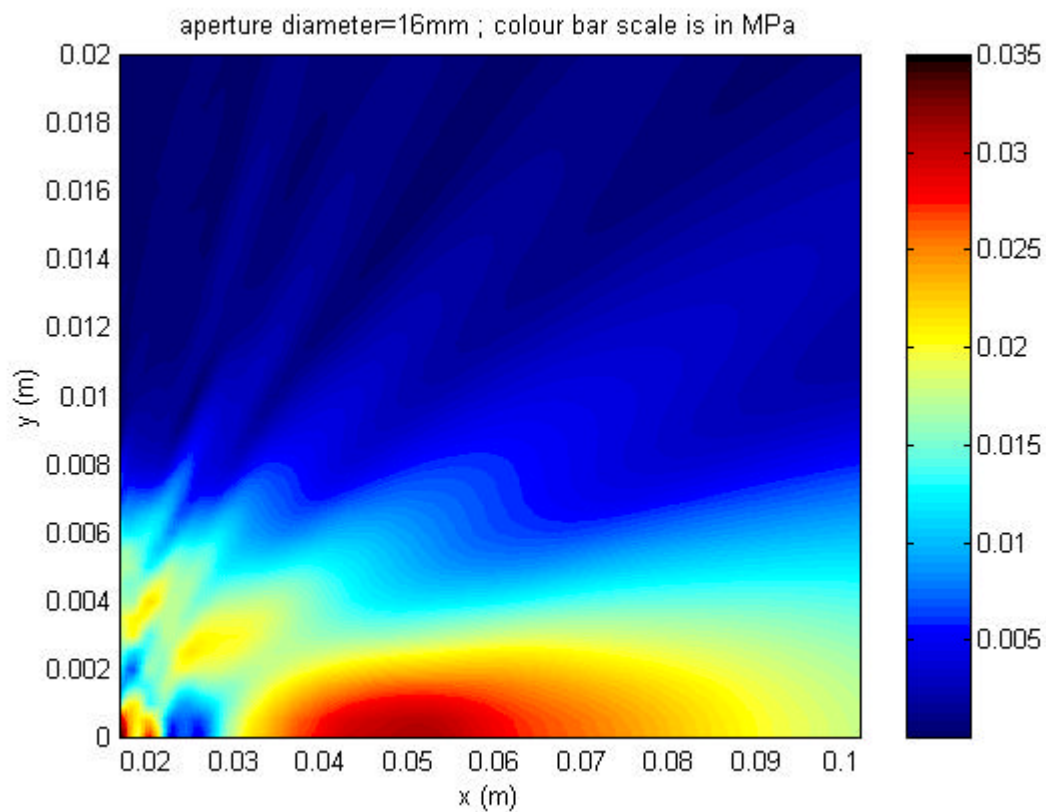


Figure 2.4: Contour plot of pressure field when a 16 mm aperture is used

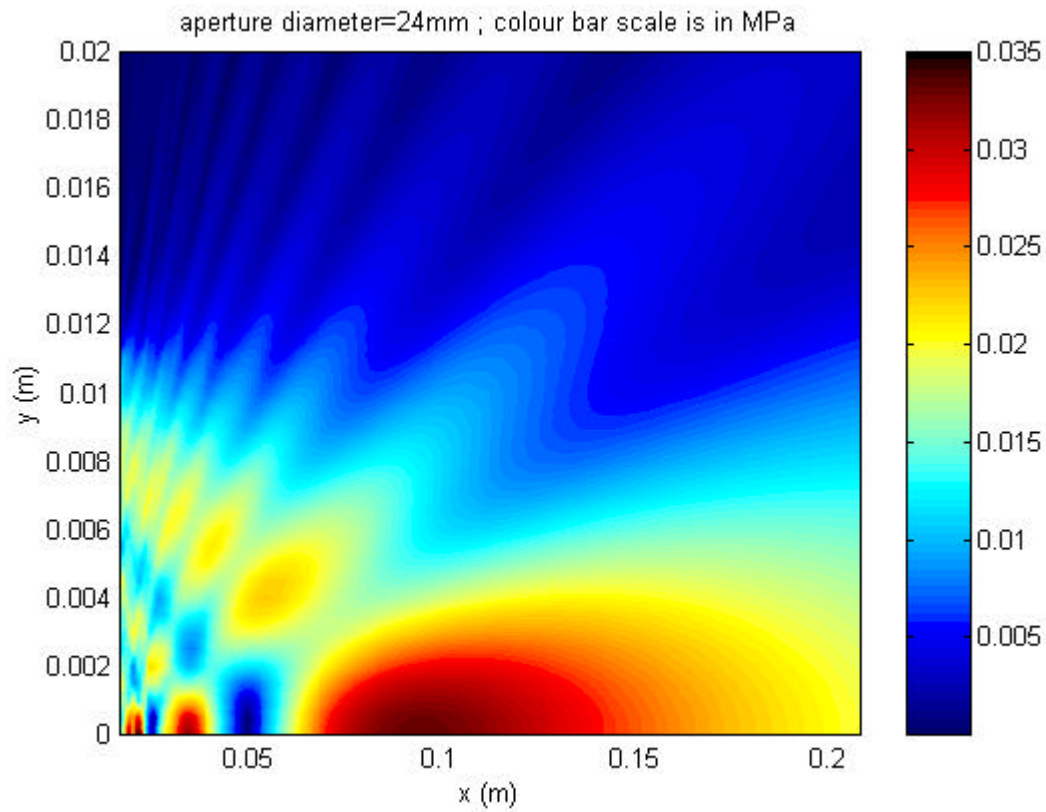


Figure 2.5: Contour plot of pressure field when a 24 mm aperture is used

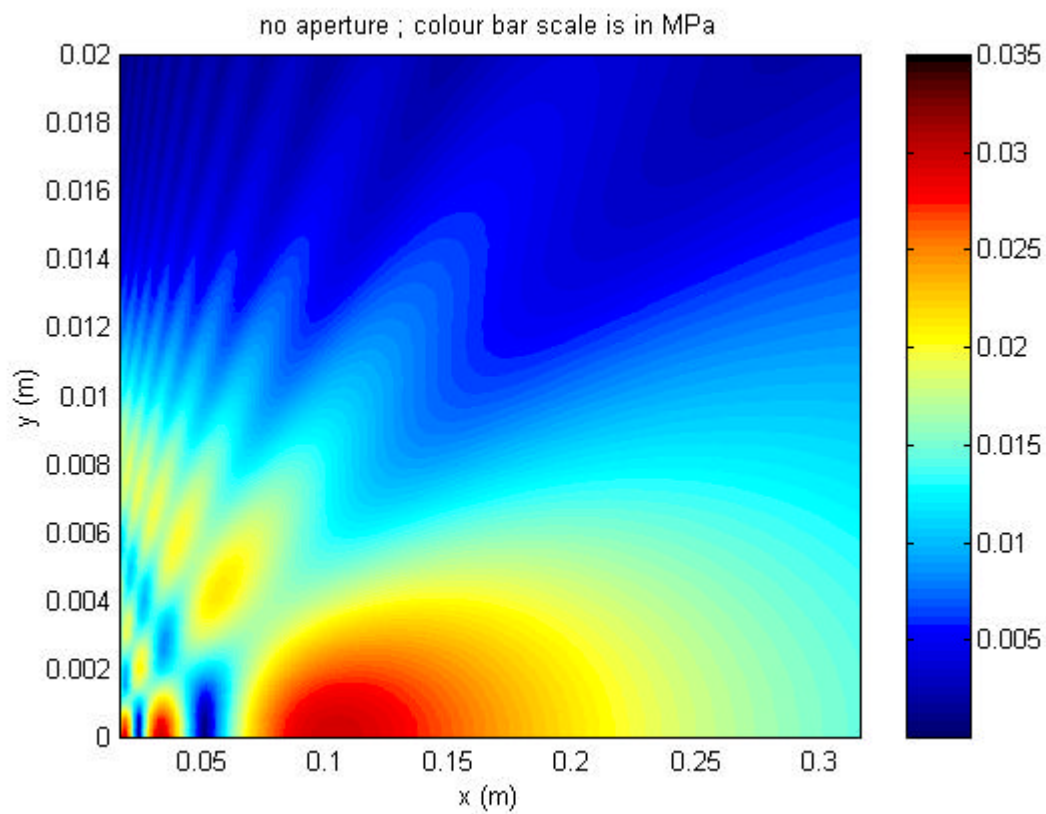


Figure 2.6: Contour plot of pressure field when no aperture is used

Figures 2.2 to 2.6 show how the diameter of the aperture will affect the sound field of a 25 mm diameter plane rigid piston vibrating at 1 MHz. In all graphs, a “hot” region is visible on-axis. This corresponds to the main pressure lobe. The amplitudes of the pressures contained in the region tend to increase with the aperture diameter. Side lobes are also visible off-axis and these tend to become more important as the aperture diameter increases.

2.3.2 Simulation of radiation force measurements as a function of aperture diameter for $ka=21, 24.5, 42$ and 55.5

2.3.2.1 Changes in configuration

Four ka values were considered for a range of aperture diameters. The configuration is similar to that described in Section (2.3.1) except for a few modifications regarding the piston radius and the driving frequency, as shown in Table 2.1.

Table 2.1: Changes in piston properties as a function of ka value

ka	Transducer radius (mm)	Frequency of oscillation (MHz)
21	5.0	1.0
24.5	7.8	0.75
42	10	1.0
55.5	8.8	1.5

Also, the transducer-aperture separation is now changed to 5 mm instead of 2.5 mm. The aperture properties remain unchanged except for the diameters under investigation which are now: 4, 5, 6, 7, 8, 9, 10, 11, 15, 18, 22 and 30 mm.

The target is assumed to be completely absorbing and has a diameter of 50 mm and is positioned at $x=19$ mm ($x=0$ corresponds to the input side of the aperture).

The rest of the piston, aperture and propagating medium properties specified in Section 2.3.1 remain unchanged.

2.3.2.2 FE considerations

A. Mesh density

Although this will depend on the hardware and the type of problem to be solved, FE models tend to generally require fairly long computational times, as well as large memory requirements for megahertz frequency calculations. Throughout the work done towards this report, three elements per wavelength were used. This is the minimum criterion in order to avoid spatial sampling errors. It was found that when a more refined mesh was used, this resulted in run times which were impracticably long (several days). In some cases, the hardware did not have enough memory to cope with the problem size.

B. Pressure gradient evaluation

The output degree of freedom in acoustic FE methods is acoustic pressure. It was seen in Sections (2.2.1.1) and (2.2.1.2) that the axial component of the particle velocity vector is needed for the evaluation of the normal radiation force. Also, both acoustic pressure and normal particle velocity are needed in order to compute the acoustic power due to the normal intensity on the target. A way to obtain the normal particle velocity is to consider the acoustic pressure gradient at discrete points throughout the radius of the absorbing target and across two parallel lines on either side of the target. Hence, if the target is positioned at $x=x_0$, the pressures would be evaluated for discrete values of R between $R=0$ and $R=b$ at $x=x_0-\Delta x_0$, $x=x_0$ and $x=x_0+\Delta x_0$ (recall that b is the target radius). In practice, Δx_0 must be small enough so that the gradient is accurately estimated but not so small so as to provide additional numerical errors due to inaccuracies in the pressure calculations. Since the pressure values will only have finite accuracy in terms of significant figures, making Δx_0 too small may result in large errors in the pressure gradient. A suitable value for Δx_0 was found to be 4×10^{-7} m. Also, it should be noted that a FORTRAN subroutine had to be written to provide pressure values to six significant figures for pressures computed within the boundary element. The default value of four significant figures resulted in quantisation errors when the particle velocity was estimated. Once these pressures are evaluated in PAFEC, a numerical value for the pressure gradient may be estimated using a MATLAB® numerical differentiation routine. The axial particle velocity may then be obtained using:

$$\hat{u}_x = -\frac{1}{j\omega r} \frac{\partial}{\partial x} \hat{p}(\mathbf{r}) \quad (13)$$

2.3.2.3 MATLAB® code for FE validation in un-apertured case

A MATLAB® routine was written to numerically evaluate the velocity potential Φ . This is done by numerically solving the double integral in equation (10) using a double quadrature routine. This enables the acoustic pressure to be determined at any point in the field using equation (11).

The gradient of the velocity potential with respect to x must be evaluated in order to compute the particle velocity at points throughout the radius of the absorbing target. In order to get an accurate estimate of the gradient at a given value of R on the target which is located at say $x = x_0$, the velocity potential is evaluated at $x = x_0 - \Delta x_0$ and $x = x_0 + \Delta x_0$. In practice, Δx_0 must be small enough so that the derivative of Φ with respect to x at a given value of R is accurately evaluated. In order to ensure this, the analytical expression for the axial particle velocity in the on-axis case was used as a reference. This is given by (18):

$$p_{on-axis}(x,0,t) = rc\hat{u}_n \left(e^{-jkx} - e^{-jk\sqrt{x^2+a^2}} \right) e^{j\omega t} \quad (14)$$

Using equation (6), it is easily shown that:

$$u_{x,on-axis} = \hat{u}_n \left(e^{-jkx} - \frac{x e^{-jk\sqrt{x^2+a^2}}}{\sqrt{x^2+a^2}} \right) \quad (15)$$

where $u_{x,on-axis}$ is the axial component on the on-axis particle velocity. These analytical expressions for on-axis pressure and axial particle velocity help provide an estimate of the error obtained in numerically evaluating expressions (11) and (13) when $R=0$.

This can provide further assessment of the accuracy of the FE model in the un-apertured case. There are three ways in which the on-axis acoustic pressure and axial particle velocity may be evaluated:

- using the analytical expressions in equations (14) and (15)
- by numerical evaluation of the velocity potential $\ddot{O}$ in equation (10) and by using equations (11) and (9)
- using the FE method.

The three sets of results for the on-axis acoustic pressure and the axial particle velocity are displayed for each ka value in Tables (2.2) and (2.3).

Table 2.2: Magnitude and phase of on-axis pressures on the target for $ka=21, 24.5, 42$ and 55.5 in un-apertured case

ka	$ p_{on-axis} $ (Pa) (analytical value)	$\angle p_{on-axis}$ (rad) (analytical value)	$ p_{on-axis} $ (Pa) (numerical value)	$\angle p_{on-axis}$ (rad) (numerical value)	$ p_{on-axis} $ (Pa) (FE value)	$\angle p_{on-axis}$ (rad) (FE value)
21	2.6529×10^4	4.8583×10^{-1}	2.6529×10^4	4.8583×10^{-1}	2.6160×10^4	5.8645×10^{-1}
24.5	2.7975×10^4	-3.6954×10^{-1}	2.7975×10^4	-3.6954×10^{-1}	2.7713×10^4	-2.4267×10^{-1}
42	2.6298×10^4	5.0202×10^{-1}	2.6298×10^4	5.0202×10^{-1}	2.5860×10^4	6.1368×10^{-1}
55.5	2.9195×10^4	-2.3212×10^{-1}	2.9196×10^4	-2.3212×10^{-1}	2.8699×10^4	1.2899×10^{-2}

Table 2.3: Magnitude and phase of on-axis normal particle velocity on the target for $ka=21, 24.5, 42$ and 55.5 in un-apertured case.

ka	$ u_{x,on-axis} $ (m s ⁻¹) (analytical value)	$\angle u_{x,on-axis}$ (rad) (analytical value)	$ u_{x,on-axis} $ (m s ⁻¹) (numerical value)	$\angle u_{x,on-axis}$ (rad) (numerical value)	$ u_{x,on-axis} $ (m s ⁻¹) (FE value)	$\angle u_{x,on-axis}$ (rad) (FE value)
21	1.7499×10^{-2}	4.8019×10^{-1}	1.7499×10^{-2}	4.8019×10^{-1}	1.7150×10^{-2}	5.7803×10^{-1}
24.5	1.8194×10^{-2}	-3.5982×10^{-1}	1.8194×10^{-2}	-3.5982×10^{-1}	1.8158×10^{-2}	-2.0000×10^{-1}
42	1.6859×10^{-2}	4.7995×10^{-1}	1.6859×10^{-2}	4.7996×10^{-1}	1.6422×10^{-2}	6.0279×10^{-1}
55.5	1.8865×10^{-2}	-2.2462×10^{-3}	1.8865×10^{-2}	-2.2462×10^{-1}	1.7751×10^{-2}	7.6284×10^{-2}

It can be seen that generally, there is agreement up to the fifth significant figure between the on-axis pressures evaluated using the analytical expression in equation (14) and those obtained by calculating the velocity potential. There are however larger discrepancies between these and the FE results (sometimes greater than 100% in the phase estimates). After closer examination, it appears that the FE calculations tend to provide better estimates

of the pressure magnitude than phase, with errors of less than 1.7% when compared against the analytical values. It turns out that when evaluating the expressions for the radiation force and power in equations (3) and (4), it is magnitude quantities which have the largest contribution. In equation (4), the cosine term does not fall below 0.975. In Figures 2.7 to 2.10, plots of the pressure across the radius of the target are shown for ka values of 21, 24.5, 42 and 55.5 in the un-apertured case respectively.

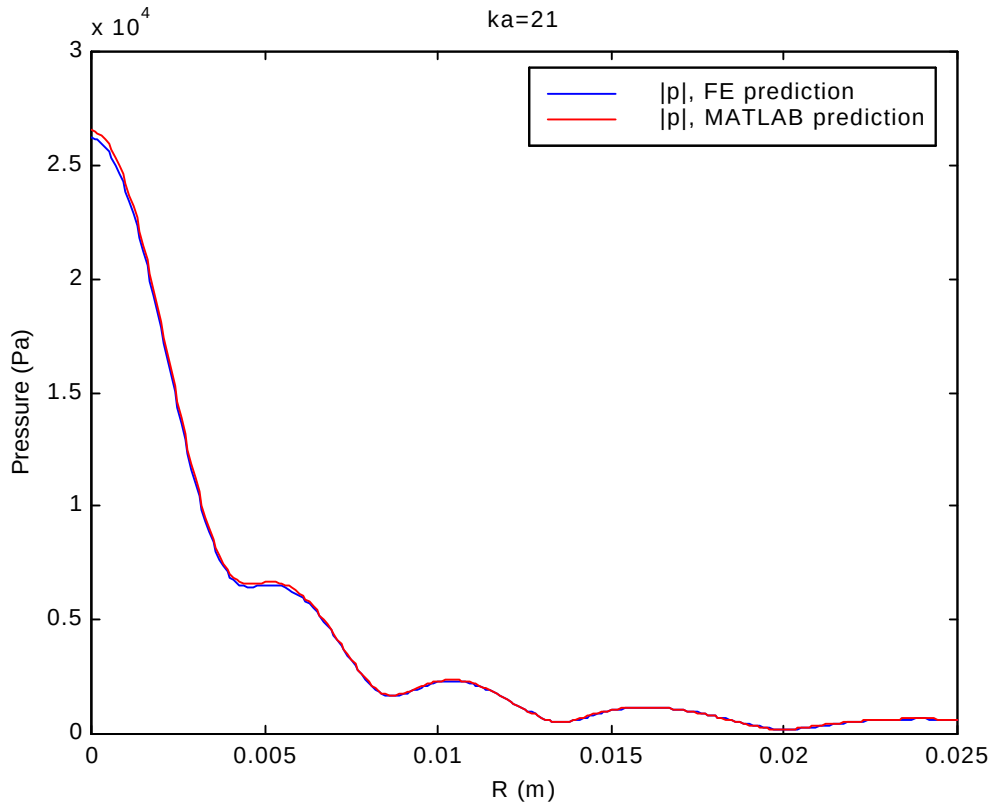


Figure 2.7: Pressure magnitude across the radius of the target in the un-apertured case for $ka=21$.

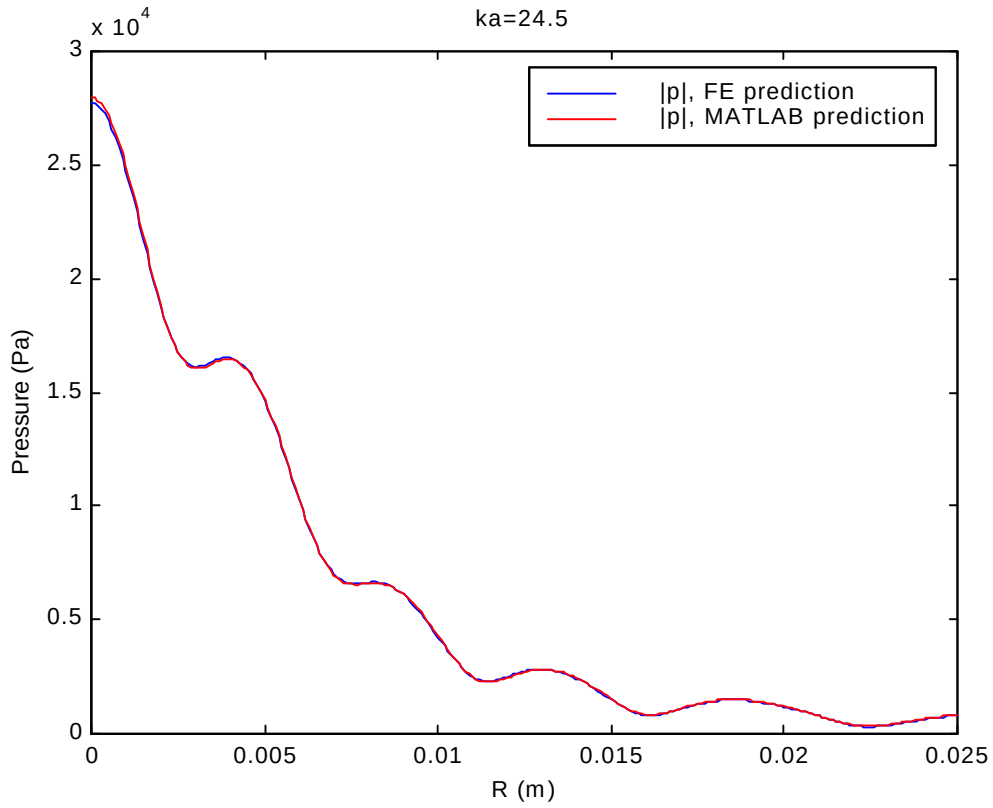


Figure 2.8: Pressure magnitude across the radius of the target in the un-apertured case for $ka=24.5$.

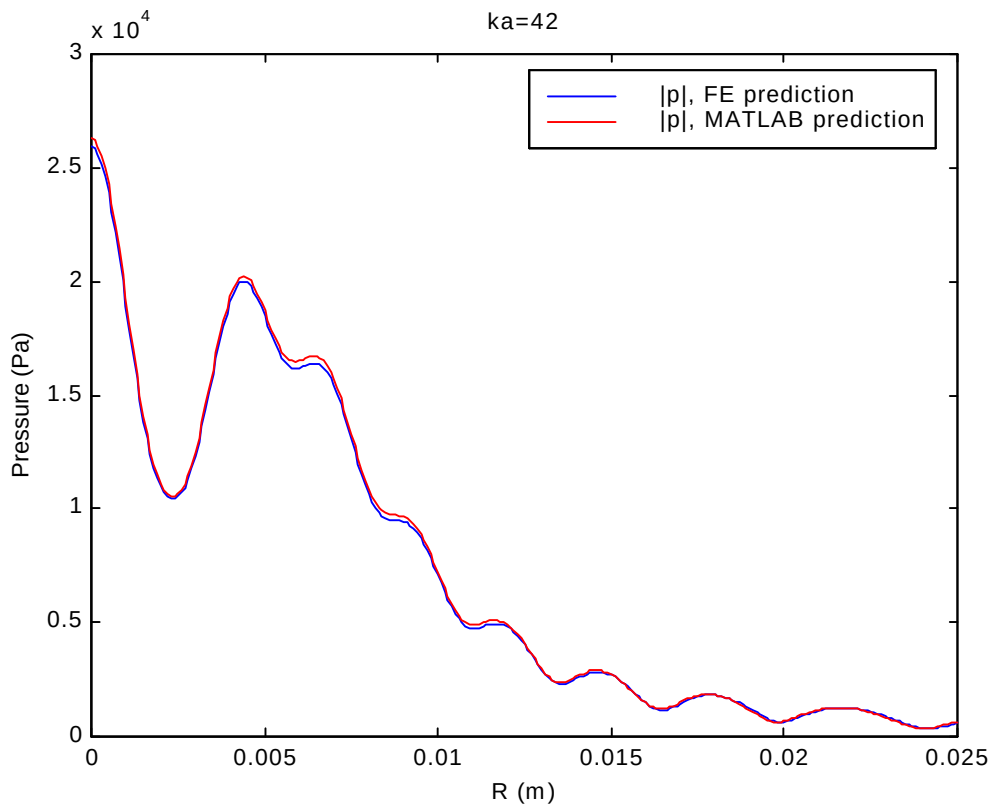


Figure 2.9: Pressure magnitude across the radius of the target in the un-apertured case for $ka=42$.

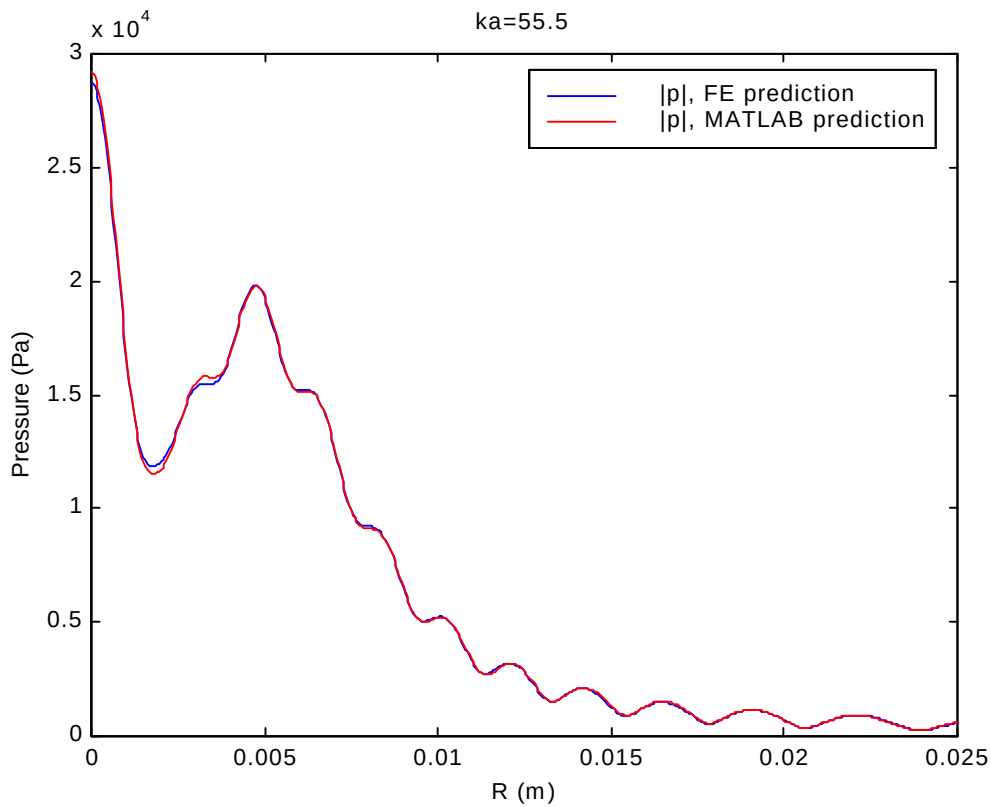


Figure 2.10: Pressure magnitude across the radius of the target in the un-apertured case for $ka=55.5$.

In order to further confirm the validity of the FE approach, plots of the quantity $I_x(x,R)R$ being integrated in equation (4) obtained using the FE method, are shown in Figures 2.11 to 2.14 as a function of the radial coordinate and compared against the values obtained by numerically evaluating the velocity potential and pressure gradient on the target in MATLAB®.

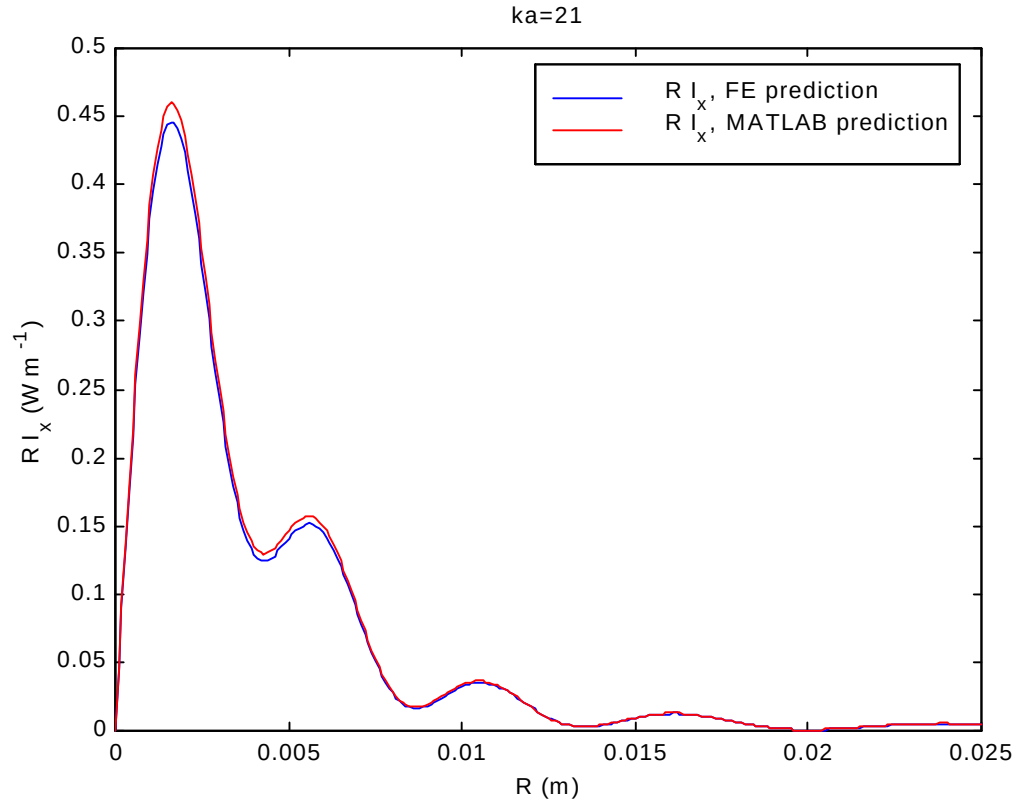


Figure 2.11: $I_x(x,R)R$ across the radius of the target in the un-apertured case for $ka=21$

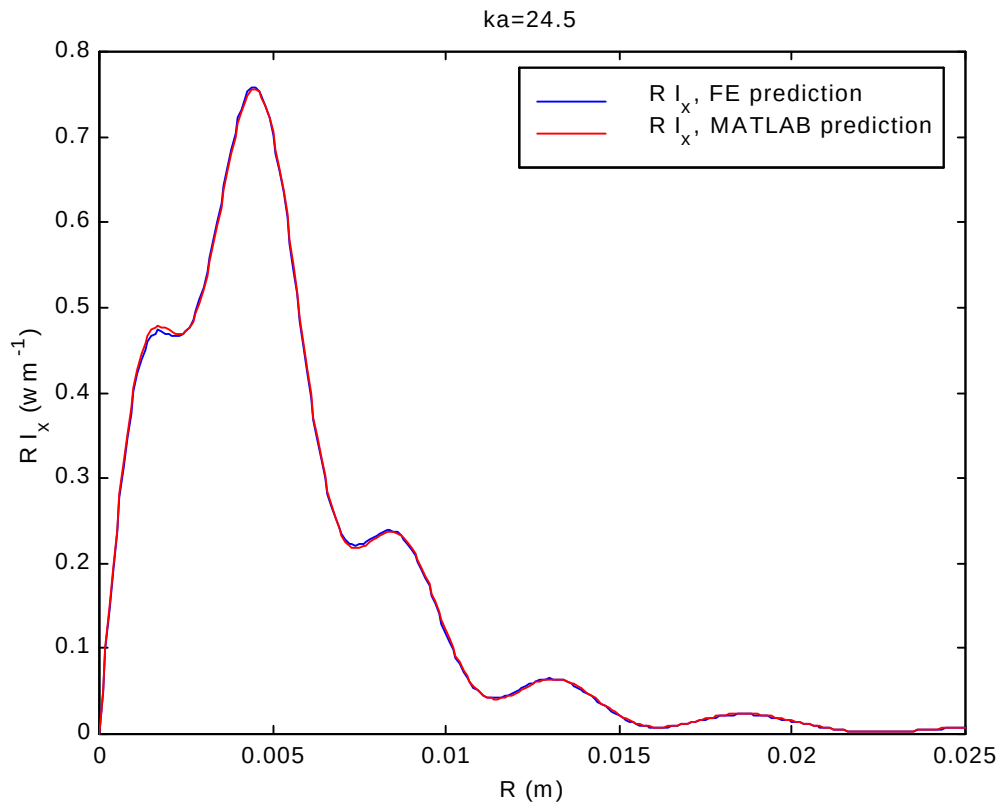


Figure 2.12: $I_x(x,R)R$ across the radius of the target in the un-apertured case for $ka=24.5$

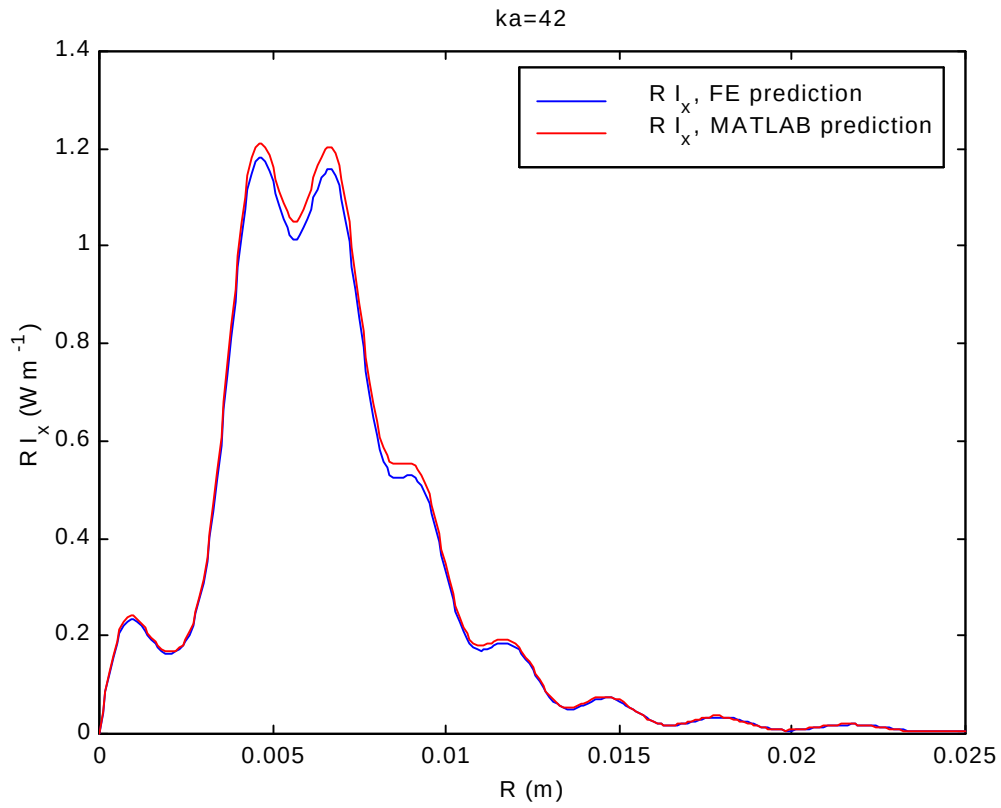


Figure 2.13: $I_x(x, R)R$ across the radius of the target in the un-apertured case for $ka=42$

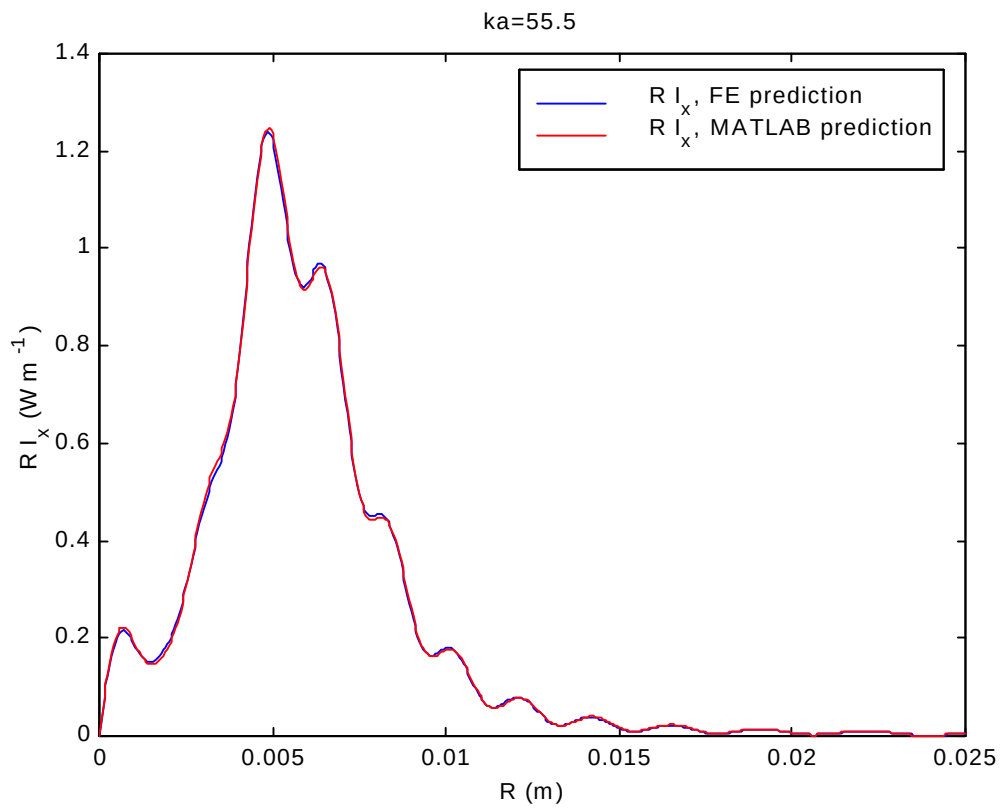


Figure 2.14: $I_x(x, R)R$ across the radius of the target in the un-apertured case for $ka=55.5$

In Table 2.4, the ratio of F_c/P is compared in both these cases and together with the analytical solution for this quantity in the case of an infinite target, as stated in equation (12).

Table 2.4: F_c/P ratio evaluated using the analytical solution for an infinite target and using the MATLAB® and PAFEC numerical solutions for a finite target.

ka	F_c/P (analytical)	F_c/P (MATLAB®)	F_c/P (FE)
21	0.9673	0.9866	0.9857
24.5	0.9701	0.9894	0.9886
42	0.9868	0.9939	0.9928
55.5	0.9881	0.9953	0.9944

Comparison between the MATLAB® and FE calculations shows a maximum difference of 0.1%. However, when compared against the analytical solution, the maximum error for both the FE and the MATLAB® calculations is close to 2%. The reasons for this lie in both the underlying assumptions in the analytical expression and the numerical errors that occur. The analytical expression assumes that the target is infinite in radius. In both the MATLAB® and FE computations, the target has a finite radius of 25 mm.

The potential sources for numerical errors are as follows. These apply for both the MATLAB® and FE computations:

- The pressures are evaluated using numerical methods, hence providing some degree of error. When comparing the on-axis pressure magnitudes obtained analytically with the MATLAB® numerical results, the maximum error in the MATLAB® prediction is $0.34 \times 10^{-2}\%$. The error in phase calculations is negligible. The errors in the FE predictions are below 2% for the magnitudes. For the phase predictions however, the FE results can show errors up to 105% when compared with the analytical on-axis values;
- These errors will be carried over when estimating the pressure gradient on the target and additional errors will occur due to the numerical method employed in doing so;
- There are a finite amount of points on the target at which the pressure and pressure gradient have been estimated, hence causing further errors when numerically evaluating the integrals in equations (3) and (4);
- The target is of finite size, so results are expected to differ with the analytical expression since $I_x(x,R)R$ has not completely decayed to zero at $R=b$ (see Figures 2.11 to 2.14).

Further investigation of the convergence criteria for the acoustic pressure in the FE model lies beyond the scope of this project. Nevertheless, it appears that when radiation force and power on the target are to be estimated, the inaccuracies in the pressure phase predictions do not significantly affect this.

2.3.2.4 Radiation force and power calculations in presence of the aperture

Using the methods described in Sections (2.2.1.1) and (2.2.1.2), the normal component of the radiation force and the power on the absorbing target are evaluated in the apertured case at three locations for each ka value; tables 2.5 to 2.8 show the radiation force values derived at the following locations:

- the aperture input;
- the aperture output;
- the target.

Table 2.5: Radiation force at aperture input, output and on target as a function of aperture diameter for $ka=21$

Aperture diameter (mm)	Radiation force at aperture input (N)	Radiation force at aperture output (N)	Radiation force at target (N)
4	7.924×10^{-7}	1.272×10^{-7}	1.148×10^{-7}
5	1.692×10^{-6}	6.011×10^{-7}	5.900×10^{-7}
6	2.478×10^{-6}	1.261×10^{-6}	1.274×10^{-6}
7	3.594×10^{-6}	2.351×10^{-6}	2.373×10^{-6}
8	5.048×10^{-6}	3.621×10^{-6}	3.649×10^{-6}
9	5.923×10^{-6}	4.736×10^{-6}	4.797×10^{-6}
10	6.653×10^{-6}	5.436×10^{-6}	5.483×10^{-6}
11	7.022×10^{-6}	6.095×10^{-6}	6.137×10^{-6}
15	7.270×10^{-6}	6.639×10^{-6}	6.685×10^{-6}
18	7.375×10^{-6}	6.917×10^{-6}	6.978×10^{-6}
22	7.418×10^{-6}	7.121×10^{-6}	7.140×10^{-6}
30	7.421×10^{-6}	7.244×10^{-6}	7.284×10^{-6}
No aperture	N / A	N / A	7.315×10^{-6}

Table 2.6 Radiation force at aperture input, output and on target as a function of aperture diameter for $ka=24.5$

Aperture diameter (mm)	Radiation force at aperture input (N)	Radiation force at aperture output (N)	Radiation force at target (N)
4	5.860×10^{-6}	7.657×10^{-7}	9.632×10^{-7}
5	7.091×10^{-6}	1.392×10^{-6}	1.782×10^{-6}
6	8.808×10^{-6}	4.524×10^{-6}	4.858×10^{-6}
7	1.098×10^{-5}	7.730×10^{-6}	8.372×10^{-6}
8	1.211×10^{-5}	9.060×10^{-6}	9.795×10^{-6}
9	1.289×10^{-5}	1.023×10^{-5}	1.073×10^{-5}
10	1.367×10^{-5}	1.172×10^{-5}	1.225×10^{-5}
11	1.541×10^{-5}	1.219×10^{-5}	1.249×10^{-5}
15	1.800×10^{-5}	1.620×10^{-5}	1.630×10^{-5}
18	1.731×10^{-5}	1.570×10^{-5}	1.579×10^{-5}
22	1.785×10^{-5}	1.679×10^{-5}	1.692×10^{-5}
30	1.804×10^{-5}	1.746×10^{-5}	1.761×10^{-5}
No aperture	N / A	N / A	1.828×10^{-5}

Table 2.7: Radiation force at aperture input, output and on target as a function of aperture diameter for $ka=42$

Aperture diameter (mm)	Radiation force at aperture input (N)	Radiation force at aperture output (N)	Radiation force at target (N)
4	1.392×10^{-6}	2.460×10^{-7}	2.671×10^{-7}
5	2.109×10^{-6}	9.583×10^{-7}	9.819×10^{-7}
6	2.552×10^{-6}	1.645×10^{-6}	1.673×10^{-6}
7	3.419×10^{-6}	2.357×10^{-6}	2.390×10^{-6}
8	4.619×10^{-6}	3.163×10^{-6}	3.205×10^{-6}
9	5.627×10^{-6}	4.366×10^{-6}	4.525×10^{-6}
10	7.423×10^{-6}	5.772×10^{-6}	5.852×10^{-6}
11	9.485×10^{-6}	7.734×10^{-6}	7.800×10^{-6}
15	1.595×10^{-6}	1.420×10^{-5}	1.440×10^{-5}
18	2.470×10^{-6}	2.206×10^{-5}	2.220×10^{-5}
22	2.968×10^{-5}	2.791×10^{-5}	2.804×10^{-5}
30	2.999×10^{-5}	2.920×10^{-5}	2.937×10^{-5}
No aperture	N / A	N / A	2.976×10^{-5}

Table 2.8: Radiation force at aperture input, output and on target as a function of aperture diameter for $ka=55.5$

Aperture diameter (mm)	Radiation force at aperture input (N)	Radiation force at aperture output (N)	Radiation force at target (N)
4	1.406×10^{-6}	8.498×10^{-7}	8.714×10^{-7}
5	2.255×10^{-6}	1.661×10^{-6}	1.691×10^{-6}
6	3.239×10^{-6}	2.586×10^{-6}	2.604×10^{-6}
7	4.180×10^{-6}	3.539×10^{-6}	3.558×10^{-6}
8	5.490×10^{-6}	4.754×10^{-6}	4.797×10^{-6}
9	6.668×10^{-6}	5.945×10^{-6}	6.048×10^{-6}
10	8.455×10^{-6}	7.625×10^{-6}	7.734×10^{-6}
11	1.054×10^{-5}	9.713×10^{-6}	9.785×10^{-6}
15	1.9170×10^{-5}	1.829×10^{-5}	1.834×10^{-5}
18	2.326×10^{-5}	2.237×10^{-5}	2.241×10^{-5}
22	2.4010×10^{-5}	2.347×10^{-5}	2.346×10^{-5}
30	2.419×10^{-5}	2.386×10^{-5}	2.388×10^{-5}
No aperture	N / A	N / A	2.396×10^{-5}

2.4 DISCUSSION

For the four ka cases examined, the calculated radiation force data has been used to attempt to derive a conversion factor to enable the determination of A_{ER} from experimental measurements using apertures. This was carried out using the following approach:

1. For the transducer of known radius, a , predict the radiation force data as a function of aperture diameter to derive a value for the theoretical A_{ER} , using the sorting analysis described previously (10);
2. Calculate the geometrical area ($= \pi a^2$) corresponding to the transducer radius a used in the particular ka case (see Table 2.1);
3. Calculate the ratio of the geometrical area in Step 2 to the derived A_{ER} in Step 1;
4. Calculate the effective transducer radius a_{eff} for each case from the theoretical A_{ER} found in Step 1 ($= (A_{ER} / \pi)^{1/2}$), and multiply by the wavenumber, k , for the particular frequency used for that model configuration to derive an effective product ka_{eff} ;
5. Plot the ratio derived in Step 3 against ka_{eff} , and fit a suitable regression to the four points to provide a value to apply as a potential correction factor to the experimentally-derived A_{ER} value as a function of real ka value.

The resulting curve for the four ka values investigated is shown in Figure 2.14.

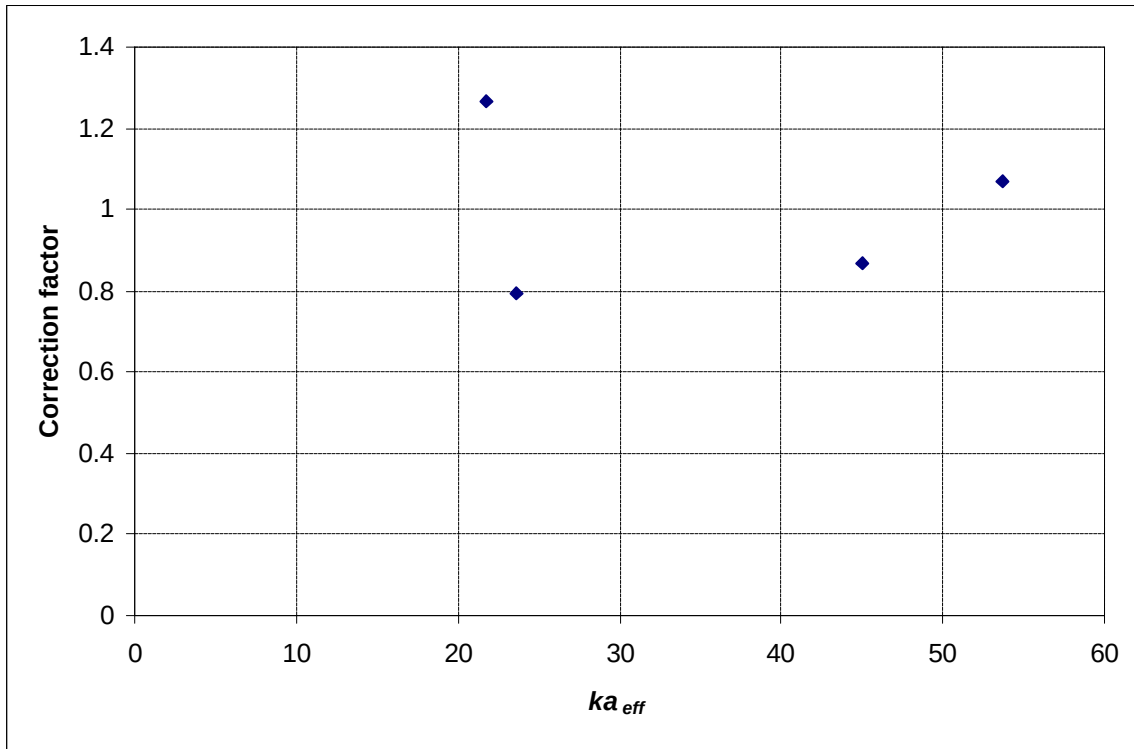


Figure 2.14: Derived correction values for each of the ka cases studied

Unexpectedly, the calculations showed that there were significant changes in the correction factor for small changes in ka_{eff} , which made the derivation of a correction factor for experimentally-derived values inappropriate. It is difficult to see how the correction factor (which would be applied as a divisor to the experimentally-derived A_{ER} value) could be less than 1, as the resulting corrected A_{ER} would then be greater than the crystal area. This is clearly unrealistic. From the data, it seems that any correction factor does not depend on the product ka_{eff} – there are separate dependences on the frequency and the effective radius.

Examining the literature, a numerical evaluation of the sound field produced by a vibrating piston with uniform and non-uniform velocity distribution has been carried out previously using the Huggens-Rayleigh diffraction integral for a wide range of ka values (21). This work fed into the production of IEC 61689, and a plot from the report is reproduced in Figure 2.15. This shows the results of the numerical evaluation carried out to derive the correction factor F_{AC} used in the derivation of A_{ER} from beam-plotting measurements, and clearly illustrates a similar dependence of the correction factor on fd ($= cka/p$), to the extent that calculations of F_{AC} for very similar fd values, but for different values of frequency and diameter, show results which range for example from 1.6 to 2.7 (for the $fd = 10$ case, which corresponds to approximately $ka = 21$).

This reinforces the view above that such a correction factor does not depend simply on the product ka , but on the frequency and the transducer radius independently. Further modelling work on a wide range of ka values and frequency/radius configurations is therefore required to produce a curve of this type that may be used to correct experimental data.

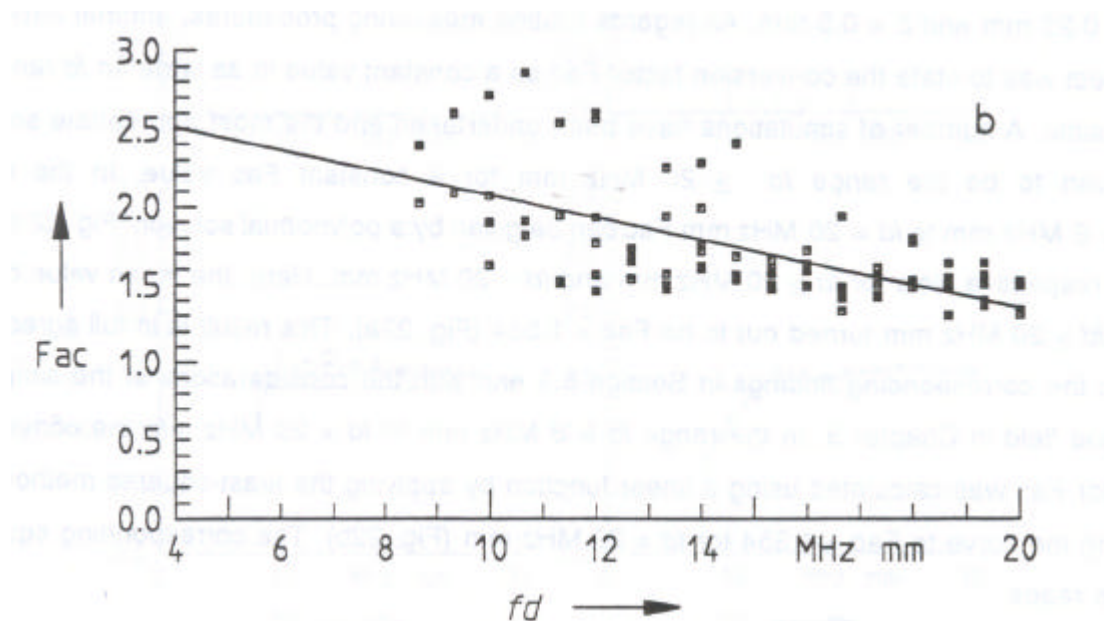


Figure 2.15: F_{AC} correction curve derivation, reproduced from (21)

2.5 SUMMARY AND CONCLUSIONS

A working model predicting the radiation force and power on an absorbing target resulting from an apertured circular plane piston rigidly vibrating in an infinite baffle and radiating into a semi-infinite fluid has been developed.

Good agreement between the FE results in absence of the aperture has been obtained against the analytical expression for the quantity F_c/P provided in Beissner (15). The acoustic power and radiation force on the target have been obtained using both results from the FE analysis and from the computation of the Rayleigh integral and good agreement between those has been obtained.

The pressure field produced by an apertured 1 MHz 25 mm diameter rigid piston vibrating in an infinite baffle has been predicted for various aperture sizes. The FE method has been used to simulate measurements of radiation force when an apertured transducer is used along with an absorbing target. This has been done for four different values of ka : 21, 24.5 42 and 55.5 and a range of aperture diameters (4, 5, 6, 7, 8, 9, 10, 11, 15, 22 and 30 mm). The axial component of the radiation force vector as well as the acoustic power due to the normal component of the acoustic intensity vector have been computed over the target. The results have been validated against the solution produced by solving the Rayleigh integral in the unapertured case.

Further investigation of the effects of FE considerations on the accuracy of the predictions may be useful in order to ensure adequate convergence of the solution. If hardware limitations were not an issue, more elements per wavelength could be used and the effect of this on the solution could be examined. This would provide further confidence in the FE results in the apertured cases, and would enable a correction curve of the type discussed above to be produced, through consideration of a large number of modelled ka cases.

It should be noted however that what has been modelled here is an idealised version of the experimental set-up used to measure radiation force. An ultrasonic transducer is unlikely to behave in the same way as a plane rigid piston mounted in an infinite baffle. The true behaviour of such a transducer is generally more complex (19), and it may be necessary to include a complete FE model of such a device in order to obtain better predictions. In a similar way, a more accurate model of the aperture may be of use, since its dynamics will affect the sound field. Despite the close impedance match of the acoustic impedance of the aperture material to that of water, when a non-plane wave is incident on the aperture, Poisson's ratio effects are likely to be an issue, and this will influence the pressure field on either side of the aperture, together with the propagated wave into the aperture. By modelling these effects, their influence on the measurement error of radiation force on the absorbing target may be estimated.

3 CHARACTERISATION MEASUREMENTS ON ENRAF TRANSDUCERS

This Section describes the reference hydrophone measurements used to characterise the four Enraf transducers used throughout the development and testing of the aperture technique. The transducer being measured was powered by the NPL reference drive system, consisting of a Hewlett Packard HP3336c synthesiser/generator, connected to an ENI 240L RF power amplifier. The transducer drive frequency was set according to values derived previously, and the transducer drive voltage was monitored via a Hewlett Packard HP3403c RMS voltmeter.

For each transducer, measurements of the field distribution were carried out using a 0.6 mm Dapco needle hydrophone to determine the effective radiating area (A_{ER}) according to the criteria specified in IEC 61689 criteria (7). The transducer acoustic axis and measurement system were aligned mechanically, an axial scan performed, and two-dimensional beam scans were carried out in 4 separated planes. The resulting data was analysed to deduce the beam-cross-sectional area (A_{BCS}) value at the 75% level for each plane, and then a linear regression was performed over the four data points. This was used to derive a value for $A_{BCS}(0)$, which was then used to produce a value for A_{ER} .

For all transducers, the full IEC 61689 characterisation was carried out at least twice. No significant differences were observed for the repeat measurements, and an average of the A_{ER} values found is presented in Table 3.1.

3.1 REFERENCE MEASUREMENTS

3.1.1 1 MHz large Enraf, serial number 16.318

The linear regression data is shown in Figure 3.1.

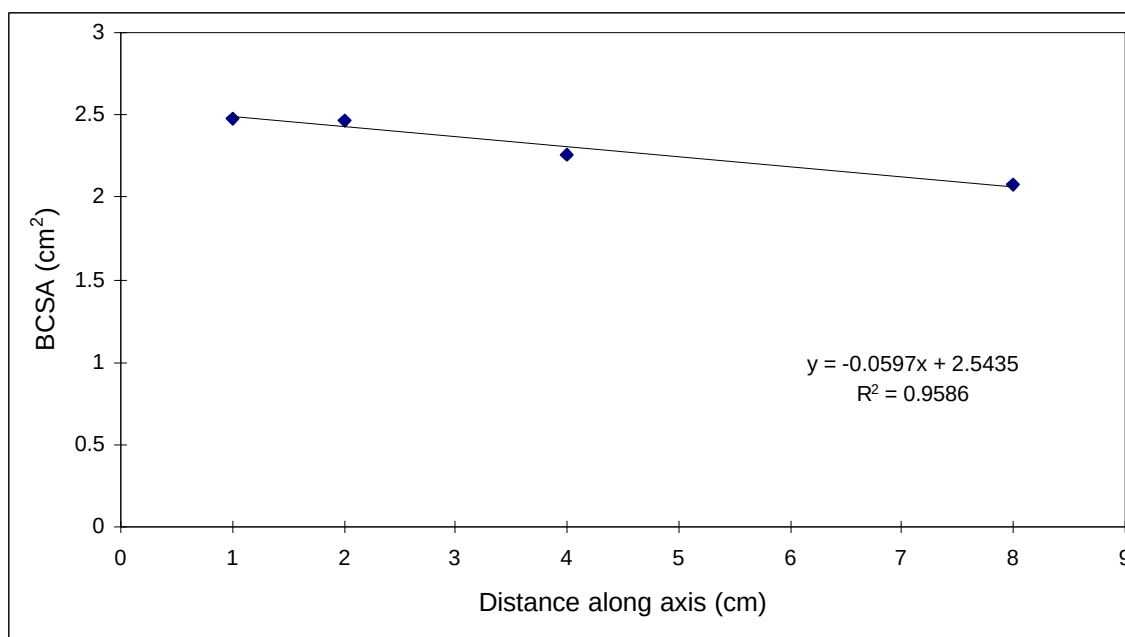


Figure 3.1: Linear regression analysis carried out on 1 MHz large Enraf transducer data

The $A_{BCS}(0)$ value in this case is 2.54 cm^2 , which after analysis, leads to an A_{ER} value of 3.44 cm^2 , with an uncertainty of $\pm 10\%$.

3.1.2 3 MHz large Enraf, serial number 05.428

The linear regression data is shown in Figure 3.2.

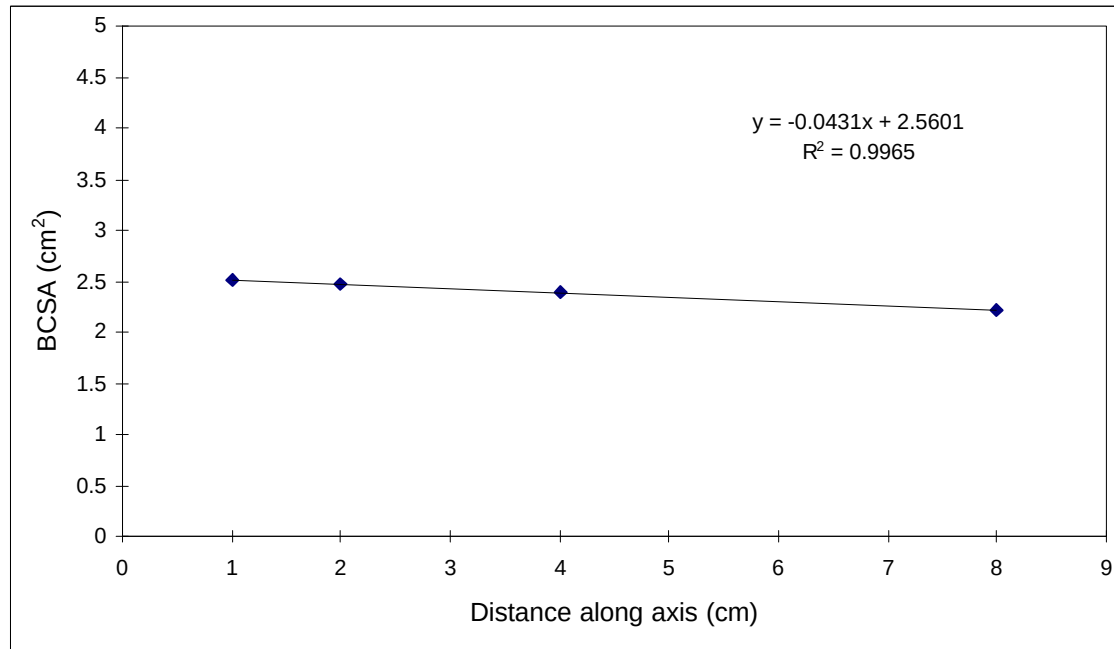


Figure 3.2: Linear regression analysis carried out on the 3 MHz large Enraf transducer data

The $A_{BCS}(0)$ value in this case is 2.56 cm^2 , which after analysis, leads to an A_{ER} value of 3.47 cm^2 , with an uncertainty of $\pm 9\%$.

3.1.3 1 MHz small Enraf, serial number 05.270

The linear regression data is shown in Figure 3.3.

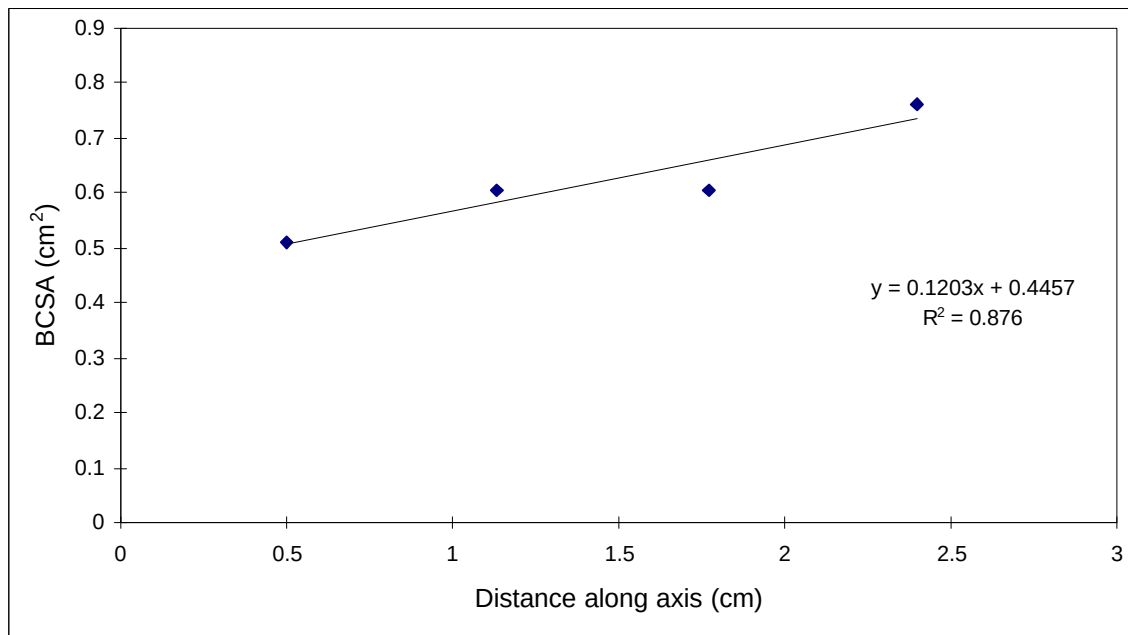


Figure 3.3: Linear regression analysis carried out on 1 MHz small Enraf transducer data

The BCSA(0) value in this case is 0.45 cm². In this instance, there is a larger uncertainty in the regression, indicated by the lower correlation coefficient. This prompted some further measurements to be carried out (see Section 3.2 below). In keeping to IEC 61689 requirements, after analysis, the derived $A_{BCS}(0)$ value leads to an A_{ER} value of 0.85 cm², with an uncertainty of $\pm 17\%$.

3.1.4 3 MHz small Enraf, serial number 12.973

The linear regression data is shown in Figure 3.4.

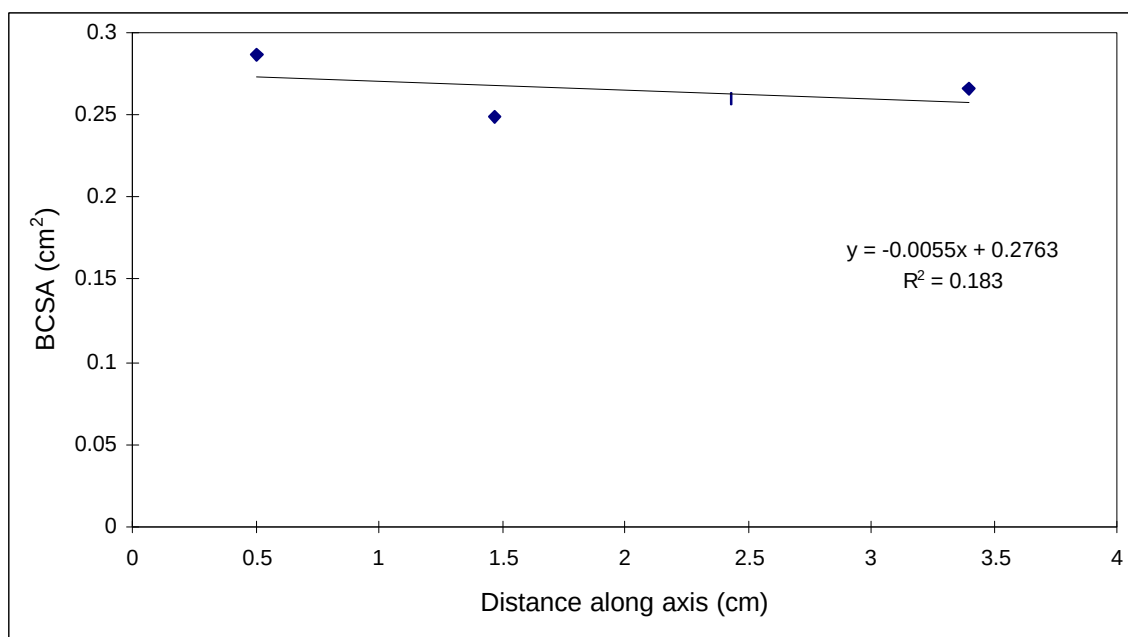


Figure 3.4 Linear regression analysis carried out on 3 MHz small Enraf transducer data

The $A_{BCS}(0)$ value in this case is 0.28 cm^2 . It is clear in this case from the very low correlation coefficient that a linear regression is inappropriate. As with the 1 MHz transducer, this prompted some further measurements to be carried out (see Section 3.2 below). However, in keeping to IEC 61689 requirements, after analysis, the derived $A_{BCS}(0)$ value leads to an A_{ER} value of 0.37 cm^2 , with an uncertainty of $\pm 20\%$. For both of the small transducers, the large overall uncertainties result predominantly from the uncertainty in the linear extrapolation performed.

3.2 SUPPLEMENTARY MEASUREMENTS

Due to the nonlinearity seen in the regressions obtained from the measurements made on the two small transducers, in particular for the 3 MHz device, additional two-dimensional scans were carried out closer to the transducer output face in each case. The additional measurements are shown in Figures 3.5 and 3.6 for the 1 MHz and 3 MHz small transducers respectively, in addition to the four ‘standard’ data points already presented above. For completeness, similar measurements were also carried out on the two large Enraf transducers, although the effect of these on the overall A_{ER} values was minimal, and so the corresponding plots are not included here.

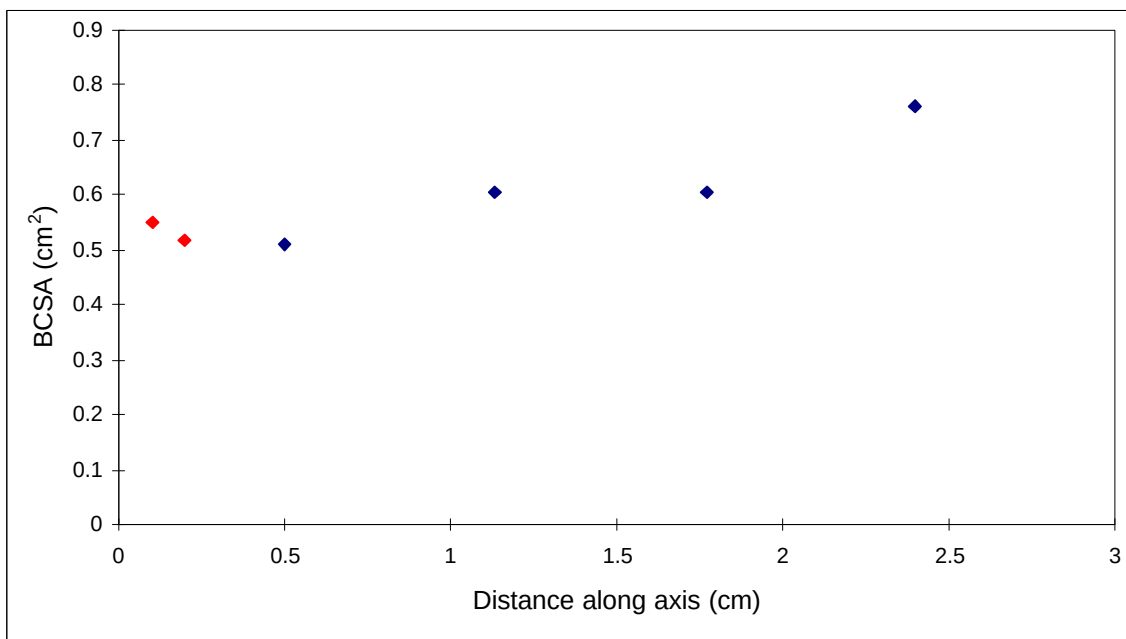


Figure 3.5: Additional beam scans carried out on 1 MHz small ENRAF transducer, shown in red. The derived A_{ER} value when the additional two points are considered in the regression increases to 0.93 cm^2 , as the $A_{BCS}(0)$ value increases. If only the closest additional scan (at 1 mm) is analysed, and the value for A_{ER} calculated simply by dividing the derived A_{BCS} value by 0.75, a figure of 0.73 cm^2 is obtained

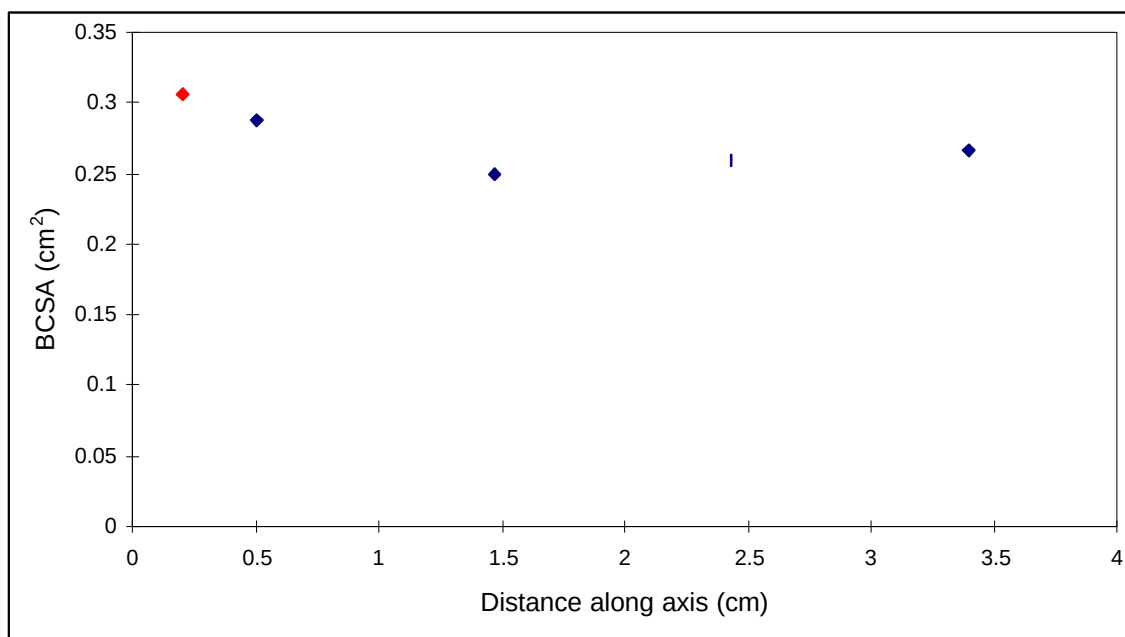


Figure 3.6: Additional beam scan carried out on 3 MHz small ENRAF transducer, shown in red. The derived A_{ER} value when the additional point is considered in the regression increases to 0.40 cm^2 . If the 2 mm additional scan is analysed, and the value for A_{ER} calculated simply by dividing the derived A_{BCS} value by 0.75, a figure of 0.41 cm^2 is obtained

3.3 SUMMARY AND CONCLUSIONS

The data obtained from all of the beam plotting measurements is summarised in Table 3.1.

Table 3.1: Summary of beam plotting measurements carried out on the four reference transducers. The right-most column refers to A_{ER} values derived from linear regressions that include the additional scans performed close to the output faces of the respective transducers. F_{AC} is the ka -related IEC 61689 scale factor by which the $A_{BCS}(0)$ value is multiplied to derive A_{ER}

Transducer	Type	Manufacturers data (cm ²)	Scan at face (cm ²)	IEC 61689 ERA (cm ²)	F_{AC} factor	IEC 61689 ERA, extra data (cm ²)
16.318	Large 1 MHz	4	3.41	$3.44 \pm 9\%$	1.354	3.46
05.428	Large 3 MHz	4	3.35	$3.46 \pm 10\%$	1.354	3.47
05.270	Small 1 MHz	0.8	0.73	$0.85 \pm 17\%$	1.906	0.93
12.973	Small 3 MHz	0.5	0.41	$0.37 \pm 20\%$	1.354	0.40

These results indicate that the IEC61689 linear extrapolation technique may be less reliable for small transducers, with the A_{ER} values derived directly (by multiplying by 1.3333) from A_{BCS} data acquired close to the transducers perhaps better estimates of the true A_{ER} values. Use of the A_{ER} based on a linear regression will probably tend to overestimate the true value of the effective radiating area for small transducers, due to the high value of F_{AC} derived. The difference is most marked, as would be expected, for the 1 MHz small transducer, which has a ka value of 21.

These reference values for A_{ER} were used as the basis for assessing the accuracy of the aperture based techniques used for determining A_{ER} .

4 COMPARISON OF APERTURE MEASUREMENTS FROM REFLECTING AND ABSORBING TARGETS

4.1 RATIONALE

Until the present project, all aperture measurements have been carried out using a balance based on a commercially-available EMS radiation force balance, which utilises a reflecting target (10). However, a recently completed project at NPL has shown that significant differences can occur between the power measured using reflecting targets, and that derived from absorbing target data (14). As would be expected, the differences are greater for small ka transducers ($ka < 25$).

The current set of NPL Apertures consists of 20 separate masks, constituting a size distribution from 4 mm – 30 mm diameter, and for 1 MHz transducers in particular, there is a strong likelihood of diffraction when using the smaller diameter masks. For instance, the notional ka value of the 4 mm diameter aperture when used with a 1 MHz transducer is 8.5. Thus, diffraction effects are expected, and are likely to cause significant underestimates of the true acoustic power when using reflecting targets. This has the effect of overestimating the effective radiating area of the transducer, due to the manner in which the data is analysed.

4.2 EXPERIMENTAL

The recently-completed EC project developed NPL's reference therapy-level balance whose design was versatile enough to be used with both reflecting and absorbing targets, by means of a cradle, on which the required target is located: see Figure 4.1.

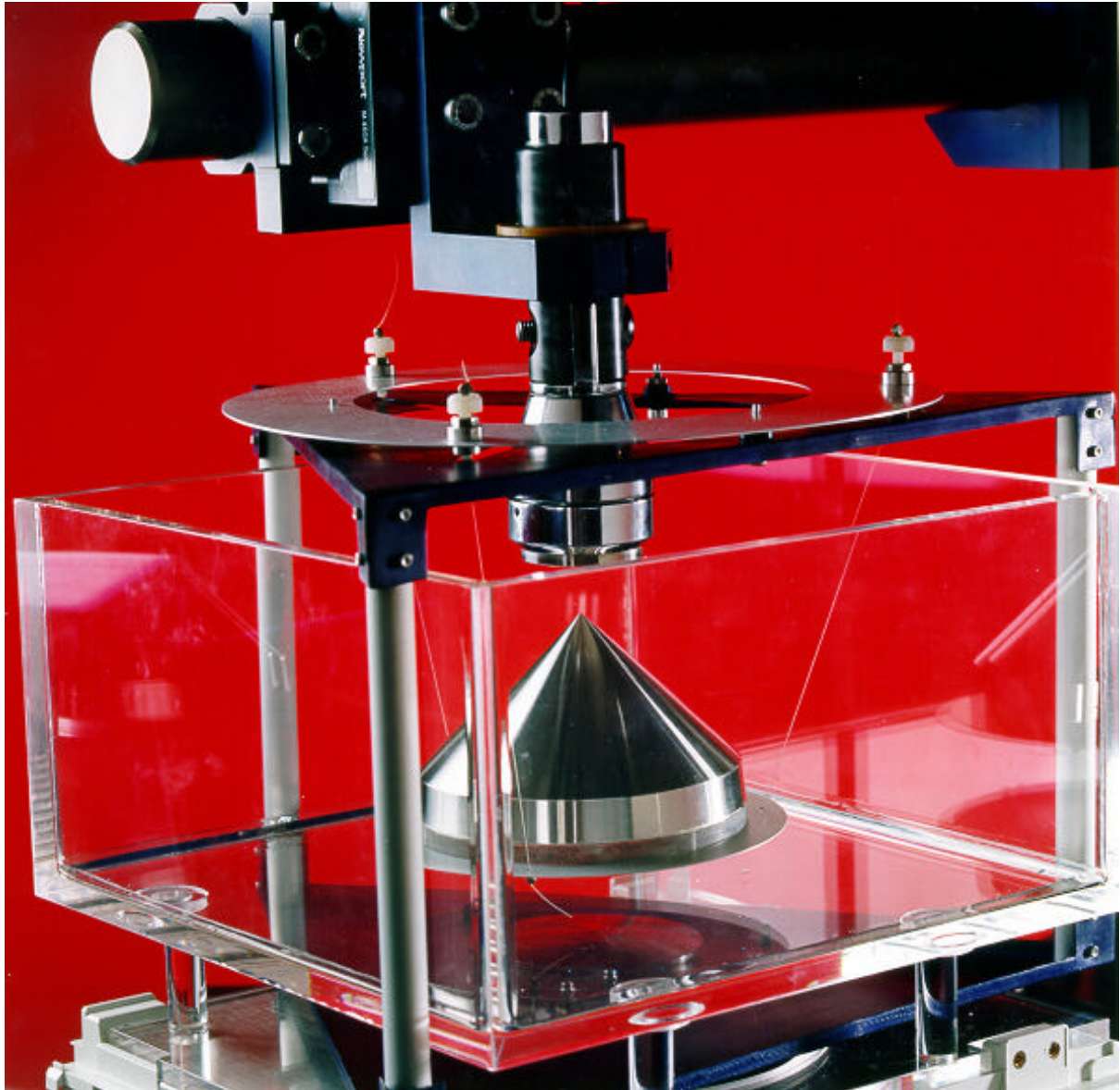


Figure 4.1: NPL Reference Therapy-Level Balance

The reflecting and absorbing targets themselves can be seen in Figure 4.2.



Figure 4.2: Reference therapy-level balance targets

To extend the capability of the balance to making aperture measurements, a special adaptor was manufactured, which consisted of a clamping piece attached to the transducer casing under which was suspended a cradle. This enabled the positioning of an aperture at a set location directly in front of a physiotherapy source. In this case, the reference Enraf transducers described in Section 3 were employed, operating at nominal frequencies of 1 MHz and 3 MHz respectively. A cross section of the transducer, adaptor and attached aperture can be seen in Figure 4.3.

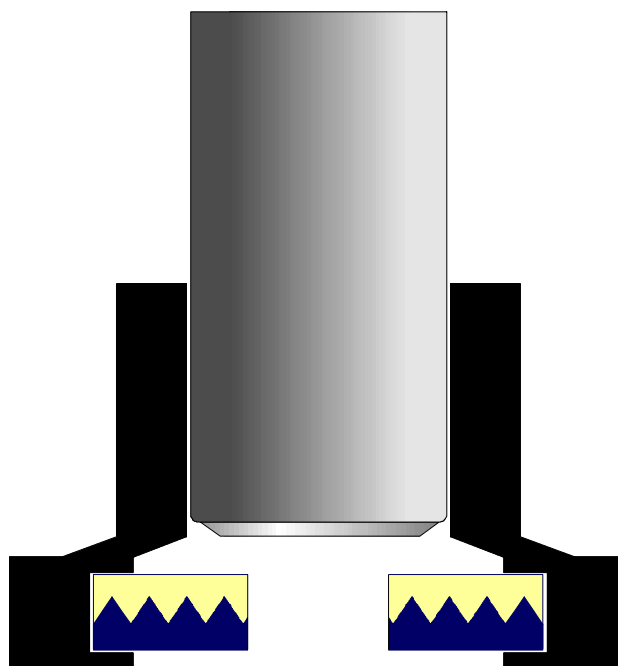


Figure 4.3: Schematic cross-section of aperture adaptor used with ENRAF transducer

The transducer under test was operated at a fixed power level of 4 W (large transducers) or 3 W (small transducers) using the NPL reference drive system described in Section 3.1. Balance readings were acquired as time histories using a program written using TestPoint, and transferred to a Pentium PC. The time history data was then analysed using a MathCad program which extrapolates the measured values back to $t=0$ (eliminating the effects of background drift).

4.2.1 Measurement protocol

To increase the statistical confidence in the measurements, data was acquired over four separate OFF-ON and ON-OFF transitions, producing eight power values for each aperture measured. The apertures were measured in a random order, and interspersed with several measurements of the 'unapertured' power, made with just the adaptor fitted. Measurements were also carried out without the adaptor in place, and showed that the effect on the measured power of the adaptor alone was less than $\pm 0.5\%$. The transducer and aperture assembly was set up at nominally the same water depth each time, with the crystal and approximately 2 mm of the transducer casing submerged. Care was taken to remove any bubbles present: the apertures themselves were immersed in a weak soap solution for at least 30 minutes prior to measurements taking place to improve their wetting.

For the reflecting target, the apex of the cone was situated approximately 5 mm below the output side of the aperture, with a similar separation adopted for the plane absorbing target. For the reflecting target case, this required some adjustment to the length of the filaments used to suspend the target ring below the gantry (see Figure 4.1 – three filaments are used to connect the two rings employed).

Once acquired, the power data as a function of aperture diameter for each transducer was analysed in the manner described previously (10), using the 'sorting' technique analogous to IEC 61689.

4.3 RESULTS

4.3.1 1 MHz large Enraf transducer, 16.318

Results are plotted in Figure 4.4 for both the absorbing and reflecting target cases, for the 1 MHz large transducer, as normalised power against aperture diameter. In each target case, the measured power values at each aperture diameter were normalised to the average of five ‘unapertured’ measurements made for that particular target configuration. The transducer drive system was set up in exactly the same manner in each case.

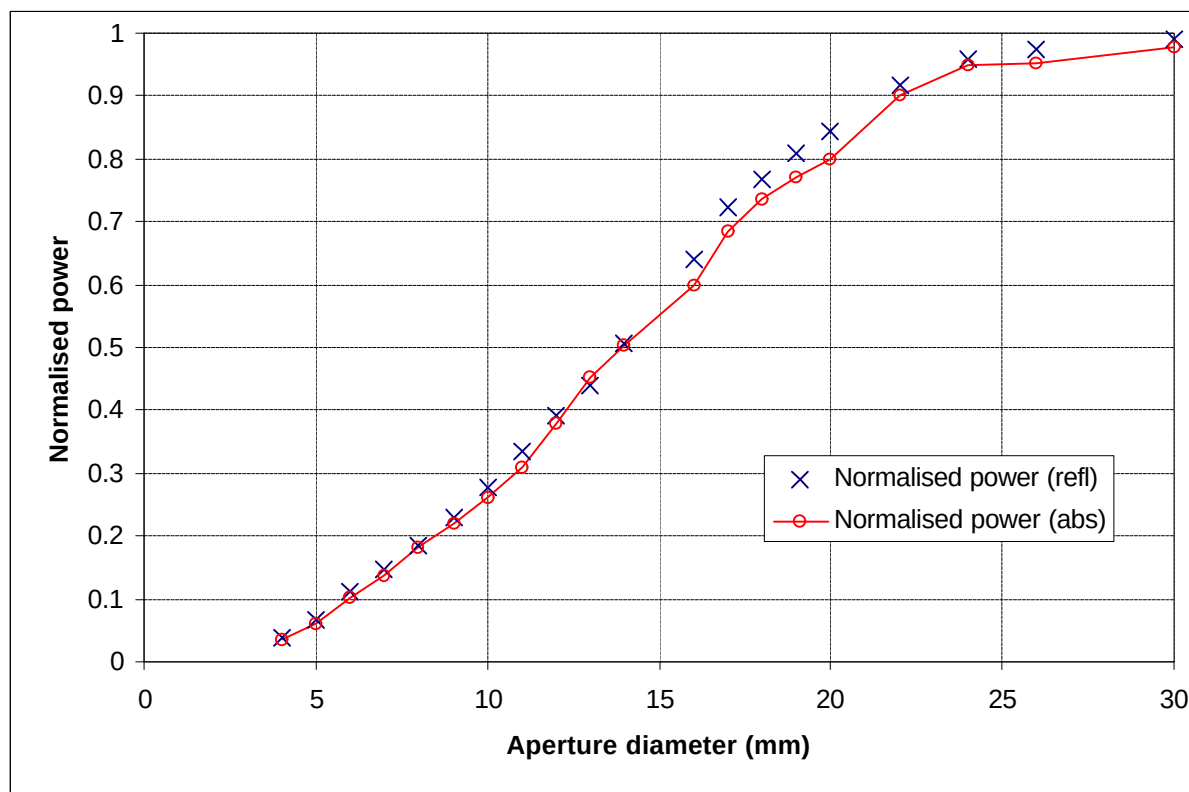


Figure 4.4: Comparison of normalised power for two target types, 1 MHz large ENRAF transducer

The agreement between the two data sets is good, with a slight ‘crossover’ between the two profiles occurring in the middle of the size distribution. The largest discrepancy between the two sets – 10% - actually occurs for the 4 mm aperture measurements, with the general level of agreement between the two sets being $\pm 2\%$ or better. The ‘unapertured’ measurements for the two target types agree to better than $\pm 0.4\%$. Note that neither data set reaches the ‘unapertured’ level for that case, showing that even the 30 mm diameter aperture has an attenuating effect on the beam.

4.3.2 3 MHz large Enraf transducer, 05.428

Results are shown for the 3 MHz transducer in Figure 4.5, with the same convention for ‘normalised power’ adopted as described above.

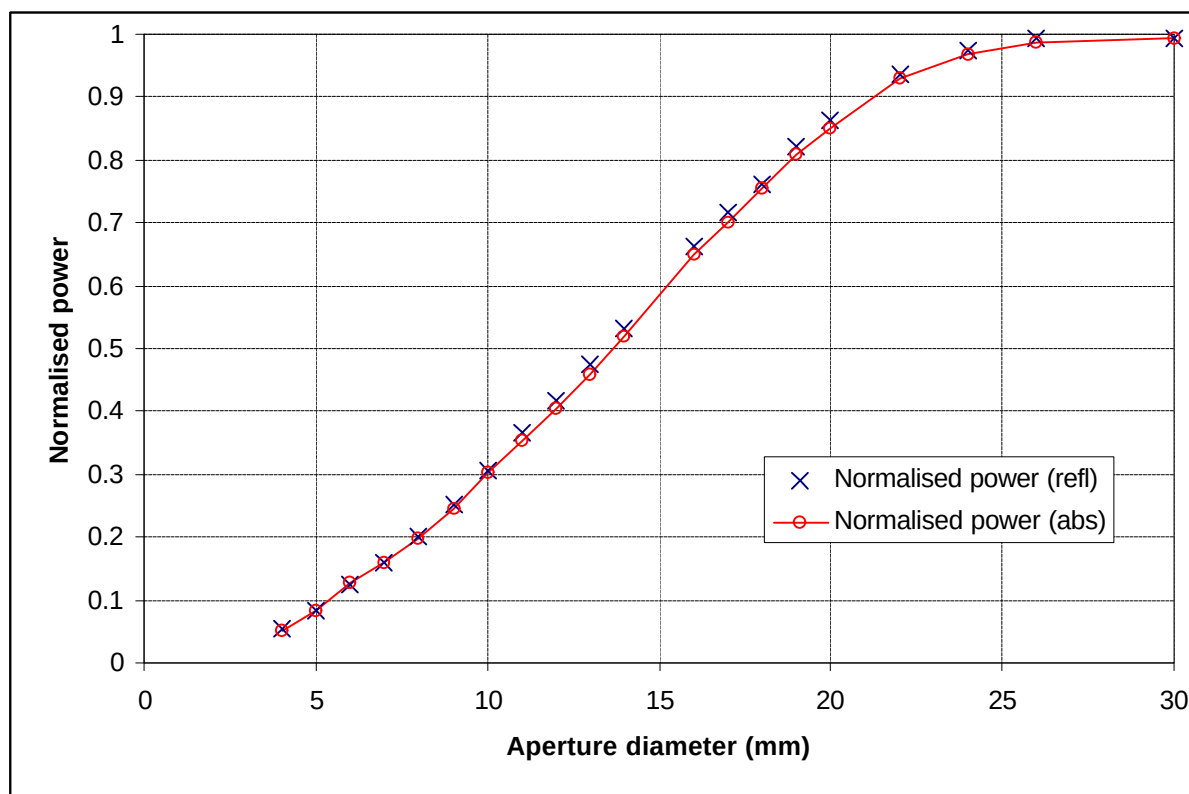


Figure 4.5: Comparison of normalised power for two target types, 3 MHz large ENRAF transducer

The figure shows that there is excellent agreement between the two target types, with the largest discrepancy being less than $\pm 2\%$. As with the 1 MHz case, the averaged ‘unapertured’ values for the two target types agree to $\pm 0.5\%$. The trend in power with aperture diameter shows a smooth variation for both target types.

4.3.3 1 MHz small ENRAF transducer, 05.270

Figure 4.6 shows the data obtained for the two sets of measurements carried out on the 1 MHz small Enraf transducer, with the same convention for ‘normalised power’ adopted as described above. In this instance, data is presented for aperture diameters up to 30 mm, as for the reflecting target measurements, there is a steady increase in the measured power even up to the largest size. This suggests that the beam produced by the 1 MHz small transducer is extremely divergent, such that it is still being attenuated by an aperture of diameter 3 times greater than the crystal itself.

It would be expected for the 1 MHz case that this divergence would cause the reflecting target measurements, particularly at small aperture diameters, to be systematically lower than absorbing target data. However, in this case, the reflecting target measurements for the smaller aperture diameters are in fact larger than the corresponding absorbing target measurements. This result was repeatable, by two different operators, and the reasons behind it are unclear.

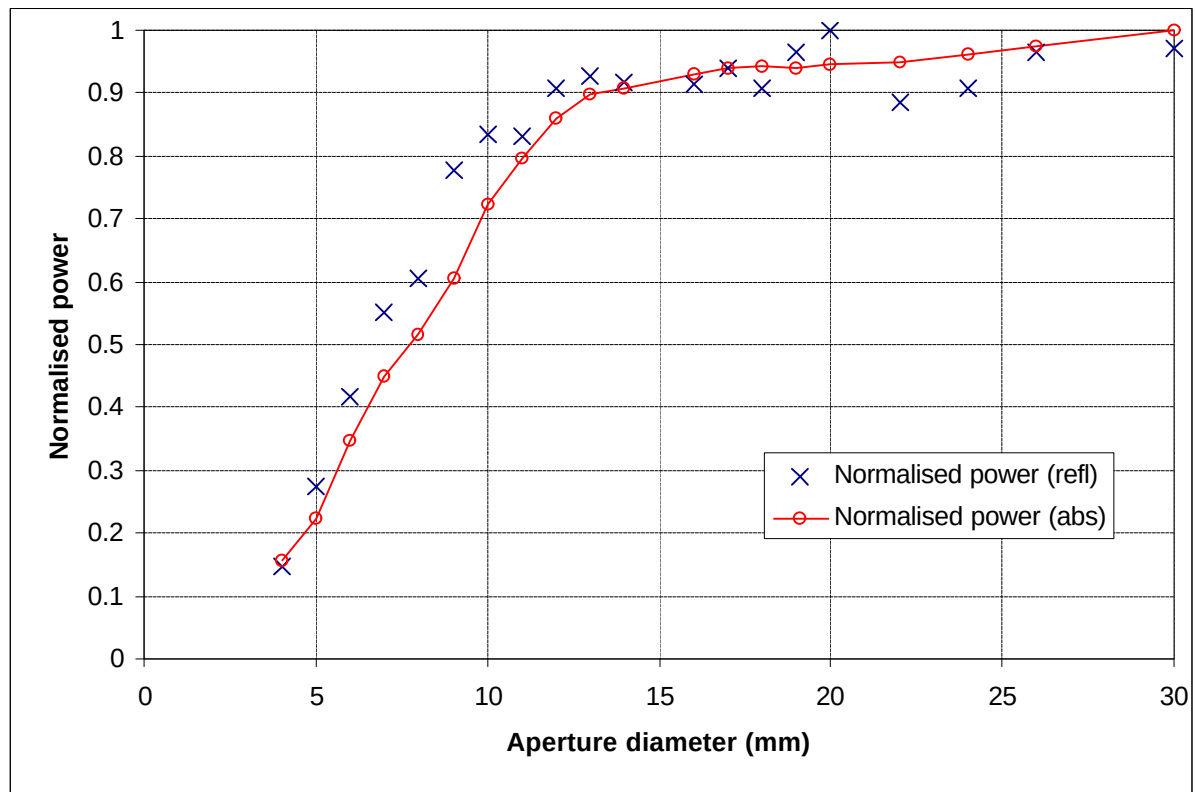


Figure 4.6: Comparison of normalised power for two target types, 1 MHz small ENRAF transducer

4.3.4 3 MHz small Enraf transducer, 12.973

Figure 4.7 shows the data obtained for the two sets of measurements carried out on the 3 MHz small transducer, with the same convention for ‘normalised power’ adopted as described above. Data is presented for aperture diameters up to 20 mm. For sizes greater than this, the normalised power as a function of aperture diameter showed no further change.

In contrast to the 1 MHz small transducer, discrepancies are seen between the two data sets in this case, in particular for the aperture diameters at the lower reaches of the range, 4, 5 and 6 mm. The reflecting target measurements are correspondingly lower than the absorbing target figures, as would be expected. Considering the 4 mm aperture case, the difference between the two target types is 26%. At this diameter, the effective ka value of the transducer, formed by the output face of the aperture, is 25.3, which has been established previously as close to the cut-off value at which significant differences can occur between reflecting and absorbing target techniques. This result is thus consistent with previous findings. At the larger aperture diameters, the two data sets converge, and the typical difference is $\pm 2\%$. For the unapertured powers, the reflecting and absorbing target set-ups agree to $\pm 2\%$.

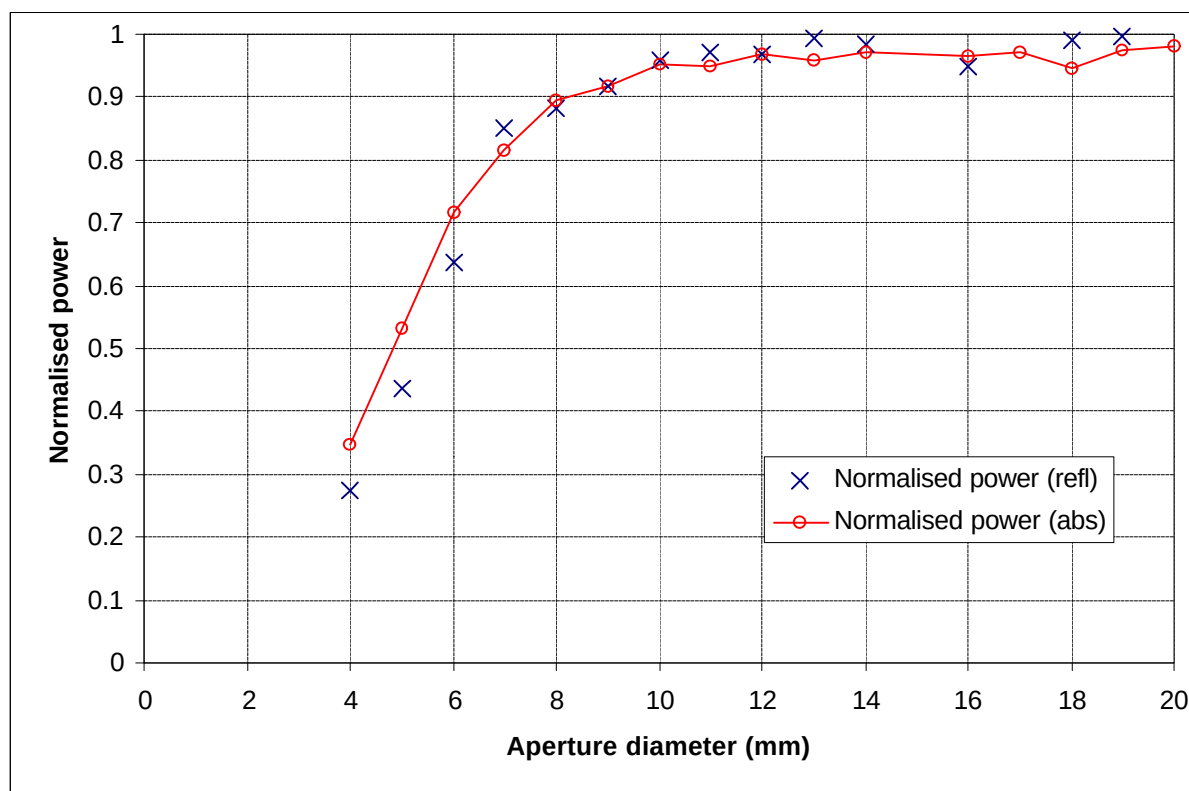


Figure 4.6: Comparison of normalised power for two target types, 3 MHz small ENRAF transducer

4.4 DISCUSSION AND CONCLUSIONS

For all of the transducers measured, the values determined for the A_{ER} from the two different target cases are shown in Table 4.1, alongside data derived from beam plotting measurements which was presented in Table 3.1. These comprise both full IEC 61689 characterisations, plus scans carried out close to the transducer output face.

Table 4.1: Comparison of A_{ER} data (values in cm^2) from 4 different measurement methods, determined for all 4 Enraf transducers

Transducer	ka value	IEC 61689	IEC 61689, extra data	Hydrophone scan close to output face (at 1 or 2 mm)	Adaptor and absorbing target	Adaptor and reflecting target
1 MHz large, 16.318	52.9	$3.44 \pm 9\%$	3.46	3.41	3.53	3.27
3 MHz large, 05.428	158.7	$3.46 \pm 10\%$	3.47	3.32	3.36	3.29
1 MHz small, 05.270	21.2	$0.85 \pm 17\%$	0.93	0.73	1.13	0.77
3 MHz small, 12.973	63.5	$0.37 \pm 20\%$	0.40	0.41	0.42	0.45

For all three transducers with ka values of 50 and above, the agreement between all four methods for a given transducer is generally good, showing that for high ka systems the aperture technique performs well. For the 3 MHz small transducer, despite there being some significant differences between the measurements carried out using the two different types of balance targets, the resulting A_{ER} values are very similar, and in good agreement with beam plotting data. For all of these cases, no significant differences are thus seen between the two target types, and so either a reflecting or absorbing target balance would be appropriate for use with the aperture technique.

The exception is the 1 MHz small transducer. From the beam plotting measurements carried out, the scan at the face is probably considered to represent the most reliable data, due to the nonlinear variation in A_{BCS} as a function of axial separation (Figure 3.5), and the reflecting target value compares favourably with this. Because of the known problems with making measurements on divergent beams with a reflecting target balance, this agreement is unexpected. The surprising differences between the reflecting and absorbing targets reported in Section 4.3.3 result in the value of the A_{ER} for the absorbing target case exceeding the reflecting target value by 47%.

Comparing the values with those found from beam plotting would suggest that the absorbing target value may be anomalous. This could be due either to a error which was repeated by both operators (for example, aperture misalignment or trapped air) or a peculiarity of the transducer field or measurement configuration, which caused the majority of the absorbing target power values to be underestimated, hence producing an overestimate in the derived A_{ER} value. Further studies are required to investigate the reasons behind the differences seen.

5 IMPROVED IMPLEMENTATION OF THE APERTURE TECHNIQUE

5.1 BACKGROUND

The original implementation of the aperture technique (10) involved the use of a radiation force balance based on a design which is commercially-available from Electro-Medical Supplies, UK (EMS). The apertures were formed individually from a prototype material and later of high quality NPL acoustic absorber (11), which meant that characterisation of a transducer required successive interchanging of the apertures using a holder positioned in front of the output face (see Figure 5.1).



Figure 5.1: Original implementation of the aperture technique, using the prototype material apertures sequentially

The original implementation necessitated the re-alignment of the transducer each time the aperture was changed, and hence also introduced an error relating to the accuracy with which the transducer could be repositioned. Also, the high air content of the absorbing material required that the aperture be weighted down below the water surface. As a result, using the necessary 15 or so apertures to measure the A_{ER} of a typical 1 MHz 25 mm diameter physiotherapy treatment head required approximately 1 hour. The agreement in measured ERA values against those determined by beam-plotting methods was generally around 11% (10). So, to improve throughput and accuracy, and hence optimise the technique, a new implementation of the method was considered essential.

5.2 CONCEPT

The original concept was formulated as shown in Figure 5.2.

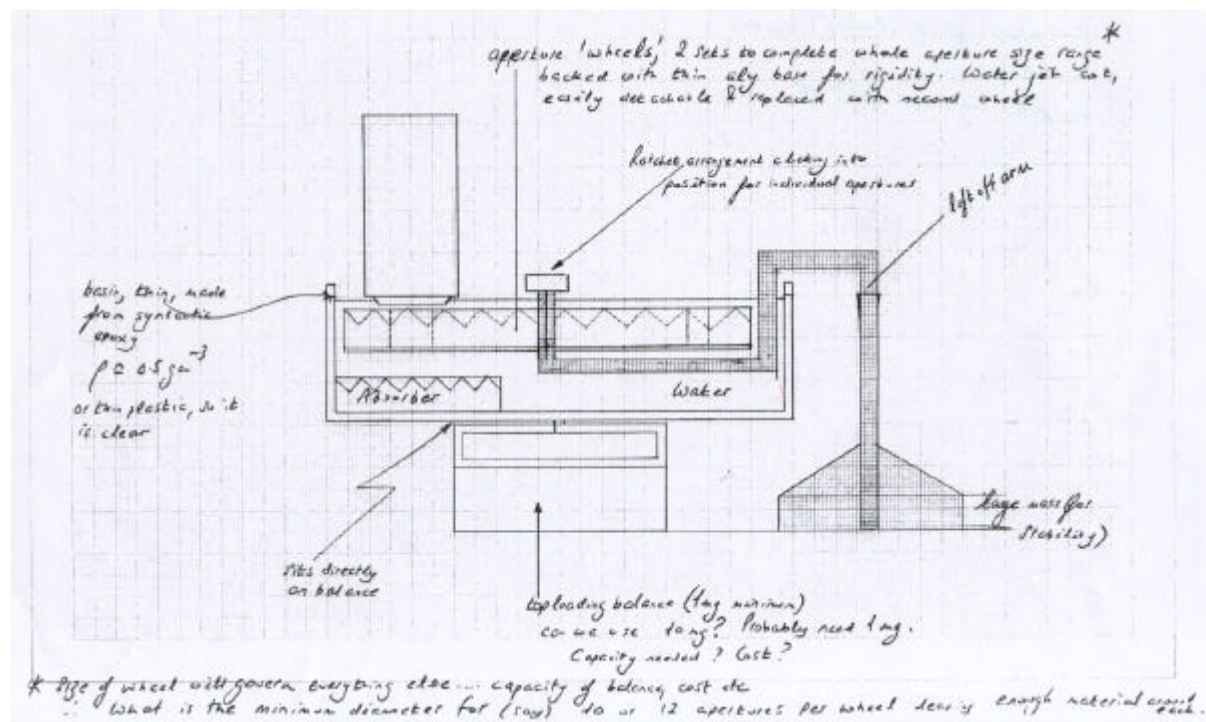


Figure 5.2: Initial design concept for new implementation of aperture method

This was referred to as the “Totally Integrated Power and Effective Radiating Area Measurement System”, or TIPERAMS for short. The envisaged wheel concept forming the apertures would allow measurements to be made of the power transmitted through different apertures without the need to lift the transducer, replace the aperture and realign the system each time. The measurement of the transmitted power would be via an absorbing target, attached to a water tank placed directly onto the balance pan without the need for a gantry. The required aperture would be selected and locked into place using a ratchet-based system – such an approach could even be automated if required.

5.3 DETAILED DESIGN CONSIDERATIONS

5.3.1 Required balance resolution

The proposed design used a top-loading balance, with the water tank containing the target placed directly onto the balance pan. Due to the diameter of the tank required to accommodate the aperture wheel (see Section 5.3.3), the water tank needed to be kept relatively shallow so that the volume of water required, and hence the weight, would be minimised. Standards requirements dictate that physiotherapy systems should be characterised down to a level of 10% of a given output power level (22), and for small systems, this can be as low as 0.1W. So, to make measurements of these low powers, a 1 mg resolution balance was required, which would provide a resolution in power measurement terms of approximately 14 mW.

5.3.2 Aperture implementation

Earlier considerations for the best way in which the apertures would be realised had included the use of a three-position slide projector-style mount placed in front of the transducer, which would allow loading and unloading of apertures without the need to remove the transducer, and also the possible use of a continuous belt, or ‘Ferris wheel’ approach, where the apertures would be successively placed in front of the treatment head under test through appropriate vertical supports and guides. Both of these approaches had the benefit of not requiring significant redesign of the original water tank configuration, but were ultimately rejected due to problems of physical dimensions and mechanical stability (latter approach) and the need to change the apertures individually (former) – although the first case might have some utility for those users who already have individual apertures and are currently using them with conventional balances.

The approach chosen was to locate the apertures on a wheel, with their centres spaced regularly about the circumference. This would then allow the wheel to be used with a simple indexer to locate them sequentially under the treatment head. The limiting dimension of a single acoustical absorber tile is 200 mm, and so this dictated the diameter of the wheel that could be used. Initially, it was considered that the full range of aperture sizes could be located on a single wheel, via two concentric rings of apertures. However, this concept was rejected because it was not possible to position all of the desired sizes on the 200 mm diameter wheel with sufficient clearance space between them, and also maintain a suitable region for attaching a mounting rod. So, it was decided to instead use two separate wheels, with aperture diameters selected in such a way as to have one wheel for ‘large’ treatment heads (from typically 17 – 25 mm crystal diameters) and one covering ‘small’ treatment heads (devices < 17 mm in diameter). This method covered the full range of aperture sizes, with some diameters present on both wheels, and incorporated an easily detachable rod for simple changing of the two. The absorbing wheel would be backed with an aluminium plate to improve rigidity.

5.3.3 Balance capacity

The choice of the ‘wheel’ aperture realisation had a direct effect on the size of the water tank required, meaning that a tank of 210 mm internal diameter would be needed. Initial estimates indicated that a depth of approximately 50 mm would be needed, and to provide sufficient capacity, a 1.2 kg tare balance was procured, Sartorius model LP1200S. Where possible, alternative lighter components were identified with a longer term view of the capacity requirement in the final system being less than 1.2 kg, in turn enabling future such systems to be based around a lower-cost balance.

5.3.4 Choice of target and diameter

The first implementation of the apertures used a balance with a reflecting target, and it was felt that for $ka < 40$ cases, diffraction could be a problem with this configuration: this would lead to underestimates of the true acoustic power and hence overestimates of A_{ER} . To lessen the impact of problems related to target geometry, it was felt that an absorbing target would thus be appropriate in this instance, even though some significant differences had been seen with absorbing target measurements when compared to beam plotting (Section 3.4). To utilise the favoured simple approach of placing the water tank directly onto the balance pan, an absorbing target was a necessity.

A formula derived by Beissner exists, (23), which provides a prediction of the diameter of an absorbing target required to intercept a plane wave beam and return an error in the radiation force of less than 2% for a given transducer-target separation distance and ka value. For physiotherapy systems, the 'worst case' is generally a 1 MHz, 10 mm diameter crystal (derived $ka \approx 21$), and in the TIPERAMS configuration, the separation distance was estimated at 25 mm. This yields a figure for the minimum required target diameter of 46 mm. From this, an effective target diameter of 50 mm was chosen. With the tank being positioned directly onto the balance pan, and also to alleviate the possibility of thermal damage by repeated use of a single piece of absorber, two nominally-identical targets were used, diametrically-opposed in the tank. This provided a well-balanced system.

5.3.5 Tank material

Given the choice of target, the water tank would not need to be lined with absorbing material. Also, if constructed from transparent material it would allow the user to see if any bubbles were present in the acoustic propagation path. So, a clear Perspex water tank of 4 mm wall thickness, 210 mm internal diameter and internal depth 35 mm was procured, with two 50 mm diameter holes cut in the base at diametrically-opposite positions 3mm from the tank edge. The absorbing targets (56 mm diameter pieces of absorber) were then glued underneath these holes with a 3 mm wide overlap all the way around, providing the 50 mm actual target diameter required.

5.4 ENGINEERING DESIGN

Once the acoustic design issues had been considered, the concept was passed to NPL Engineering Services, who considered the mechanical design and manufacturing aspects.

5.4.1 Indexing

In particular, they provided a solution for the indexing, with an integrated unit based upon a spring-loaded ball-bearing which located into precision-drilled holes in a rotatable plate. The use of two absorber wheels, with the apertures positioned in a single ring meant that there was space for 16 apertures on each wheel. However, two key aspects in the aperture-based characterisation technique are the determination of the 'free' or 'unapertured' power, carried out in the absence of an aperture, and also the 'zero aperture' or 'blank' measurement which is used to measure the effect of any electrical noise produced by the treatment head, which has been seen to affect the balance mechanism and cause significant overestimates of the output power for some commercial systems.

The need for these two measurement types meant that the wheel design was amended to include a removable U-shaped absorber piece of 40mm width, with three small support tabs formed from the aluminium backing plate used to support the piece when the 'zero aperture' measurement was made. As a result, the number of apertures on each wheel was reduced to 14, on an equal angular distribution, with the resulting 'double sized' gap used to house the removable slot. Consequently, the spacing of the holes on the indexer was adjusted to the non-regular spacing required.

5.4.2 Wheel and transducer support

The support for the wheel and indexer was best realised by a 'goal post' approach, anchored either side of the balance to a heavy base plate. This provided the most stable support for the

system, and was constructed from 50 mm square section aluminium frame. Based on previous experience, the use of a heavy-based retort stand and clamp provided ample support and positioning capability for the treatment head under test to be located with sufficient accuracy over the aperture and target.

5.5 SOFTWARE CONTROL

One advantage of using a Sartorius balance was that the NPL-developed reference therapy-level balance (Figure 4.1) utilises a similar balance of lower capacity. As a result, the software routines for balance time history acquisition developed in TestPoint® for that system were used for the TIPERAMS facility, with only some minor modifications necessary to accommodate the difference in balance specification. The program records the measured mass at 0.1s intervals, and passes the data to a graphing routine, which may then be interrogated to retrieve the raw data. Analysis routines produced in MathCad® for the reference balance were also used with TIPERAMS, to derive values for the emitted power from the raw time history data.

5.6 FINAL SYSTEM

The final system is shown in Figure 5.3.

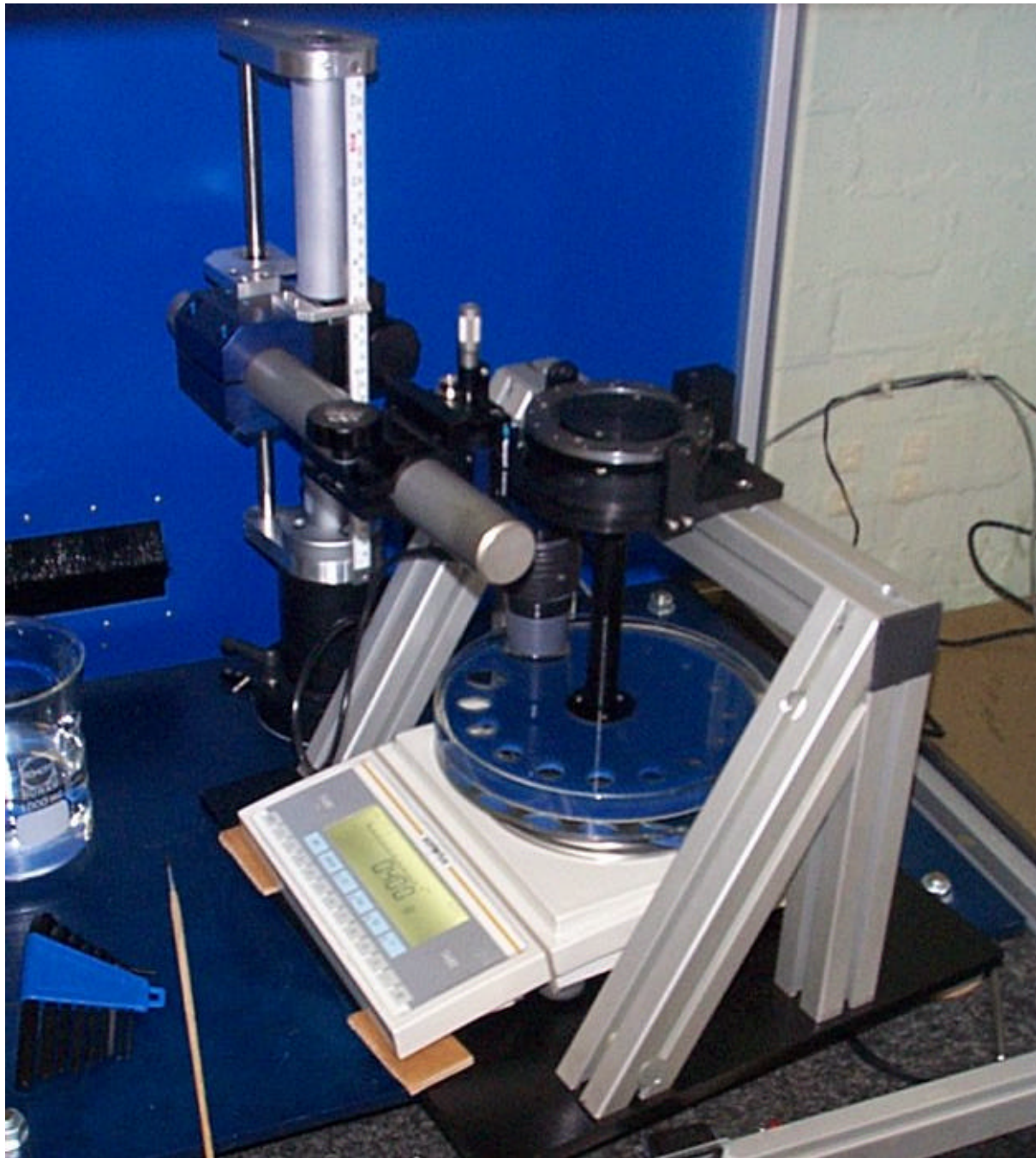


Figure 5.3: Realisation of TIPERAMS system

5.7 ACCEPTANCE TESTS

Initially, the ability of the system simply to measure ultrasonic power was tested using a calibrated NPL continuous-wave checksource, operating at a nominal power level of 1 W, at a frequency of 3.5 MHz. The Sartorius balance was set up on the bench, levelled as required and the Perspex tank with the glued absorbing targets positioned symmetrically on the balance pan. The tank was filled with degassed, deionised water, and the checksource transducer positioned over each target in turn. A series of switch-on, switch-off cycles were carried out, typically for 10 seconds duration each, and the balance display recorded. The change in mass observed was just less than 70 mg in each case, confirming that the system appeared to be working correctly. The balance response was independent of which of the

two targets were used, and was also tolerant of deviations in the symmetrical positioning of the targets to a limit of around ± 5 mm.

Two other important observables were that the system was susceptible to external vibrations, which caused ripples on the water surface and fluctuations in the balance display, and also that there was a steady background decrease in the mass of approximately 1 mg per second, which was almost certainly due to evaporation from the large water surface area. The effect of this background change was removed by the use of the software control program to store the time history of the balance reading, and the analysis routines that extrapolated the measured power back to time $t=0$.

After the initial confirmation that the system measured acoustic power in the manner expected, the 'large transducer' wheel was set up in the tank, and the checksource used again at the 1 W setting. The measured power clearly decreased as progressively smaller aperture diameters were positioned in front of the transducer. Investigating the acquired time histories showed significant disturbances when the wheel was being repositioned, resulting in a settlement time of some 10 seconds needed after the required aperture was located in front of the transducer. When located on a stable base, and with appropriate draft shielding, the system was able to resolve powers as low as 70 mW with a random uncertainty of around 15 %.

5.8 SYSTEMATIC MEASUREMENTS ON REFERENCE TRANSDUCERS

For the systematic evaluation of the system, measurements were made on the same 4 reference Enraf transducers (see Table 4.1), powered by the dedicated drive system described previously.

5.8.1 Measurement protocol

The findings from the initial acceptance tests, and from previous work formed the basis of the protocol adopted. The following steps were taken:

1. (one hour before starting measurements) - Switch on the drive electronics and submerge the wheel to be used in a vessel containing deionised water with a few drops of washing up liquid;
2. Switch on and level Sartorius balance; position empty tank evenly on the balance pan and attach aperture wheel to indexer rod. Adjust positions of balance, support and tank such that the aperture wheel has an even gap of 5 mm from the edge of the tank on all sides, and is approximately 3 mm from the bottom of the water tank;
3. Rotate the aperture wheel on the indexer such that the largest aperture available is at the "3 o'clock" position, and adjust the orientation of the tank to ensure that the absorbing target is positioned coaxially over the target;
4. Fill the water tank with freshly-drawn degassed, deionised water to a level of around 3 mm below the top of the wheel, and remove as many visible bubbles as possible from the underside of the wheel using a paintbrush;
5. Attach the transducer under test to the clamp and mount, and lower it so that it is just above the largest aperture. Align the transducer coaxially over the aperture by

eye, and use a miniature spirit level on the transducer or mount to ensure that it is level;

6. Back the transducer off to a distance of around 5 mm from the aperture wheel, and top the water level up so that the output face is covered sufficiently. Using a paintbrush if required, ensure that there are no bubbles inside any of the apertures or on the transducer face, and move the indexer around to the 'unapertured' position – remove the slot-in piece if required ;
7. Enter operator details into TestPoint® software and carry out investigation of required drive level settings: use the appropriate frequency and approximate power values of 4 W for large transducers and 2 - 3 W for small devices. Record the required drive settings and the measured voltage levels.
8. Measure the water temperature, and perform the first 'unapertured' measurement as follows: allow 10 seconds settlement time, switch ON and leave for 10 seconds, switch OFF and leave for 10 seconds, repeat three more times; allow 10 seconds settlement at end. Store time history data as a Microsoft Excel spreadsheet with an appropriate filename.
9. Randomise the order of the subsequent aperture measurements, interspersing large and small sizes to minimise the likelihood of thermal damage to the target due to prolonged exposure of high powers. During the course of the 14 aperture measurements, 4 further measurements of the 'unapertured' power are required. Check for, and remove, any bubbles as required. Save each measurement as a separate spreadsheet.
10. Analyse acquired data using MathCad® calculation software, and print out results sheets for each case.

5.8.2 Measurement data and analysis

5.8.2.1 1 MHz large transducer

Figures 5.4 and 5.5 show a typical time history and the measured power for the 1 MHz large Enraf transducer as a function of aperture diameter respectively.

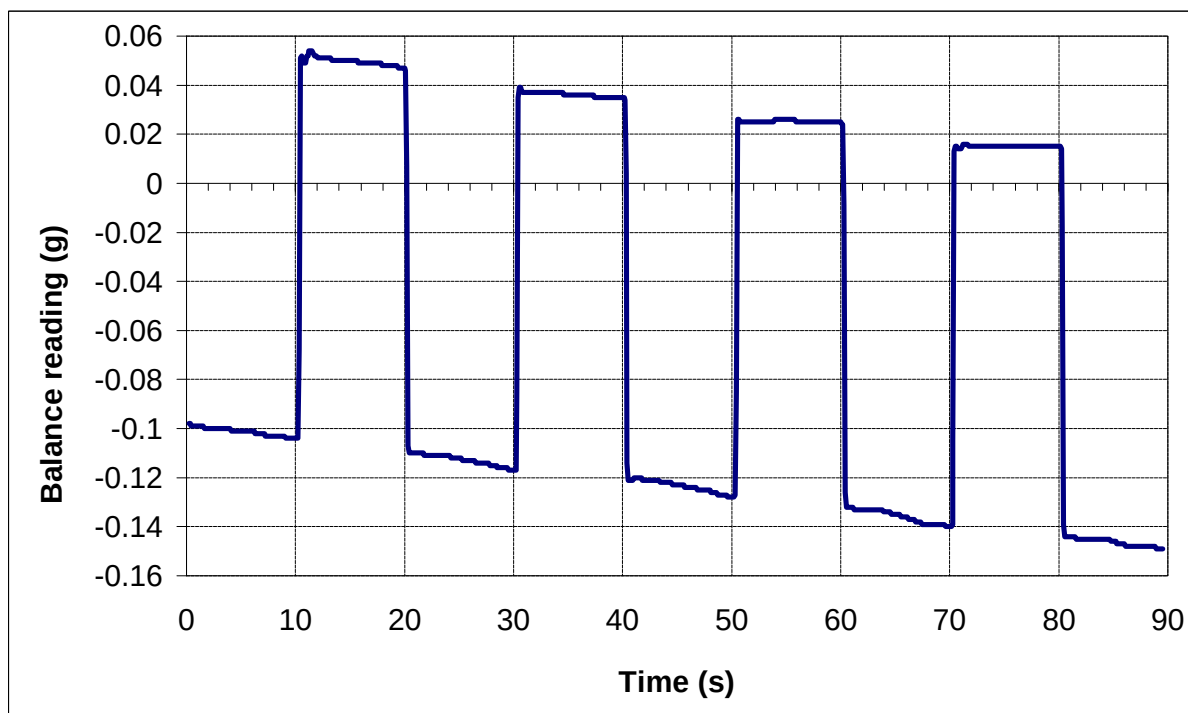


Figure 5.4: Time history of balance display, measured from a 1 MHz 25 mm diameter crystal Enraf transducer operating at 4 W, propagating through the 16 mm diameter aperture

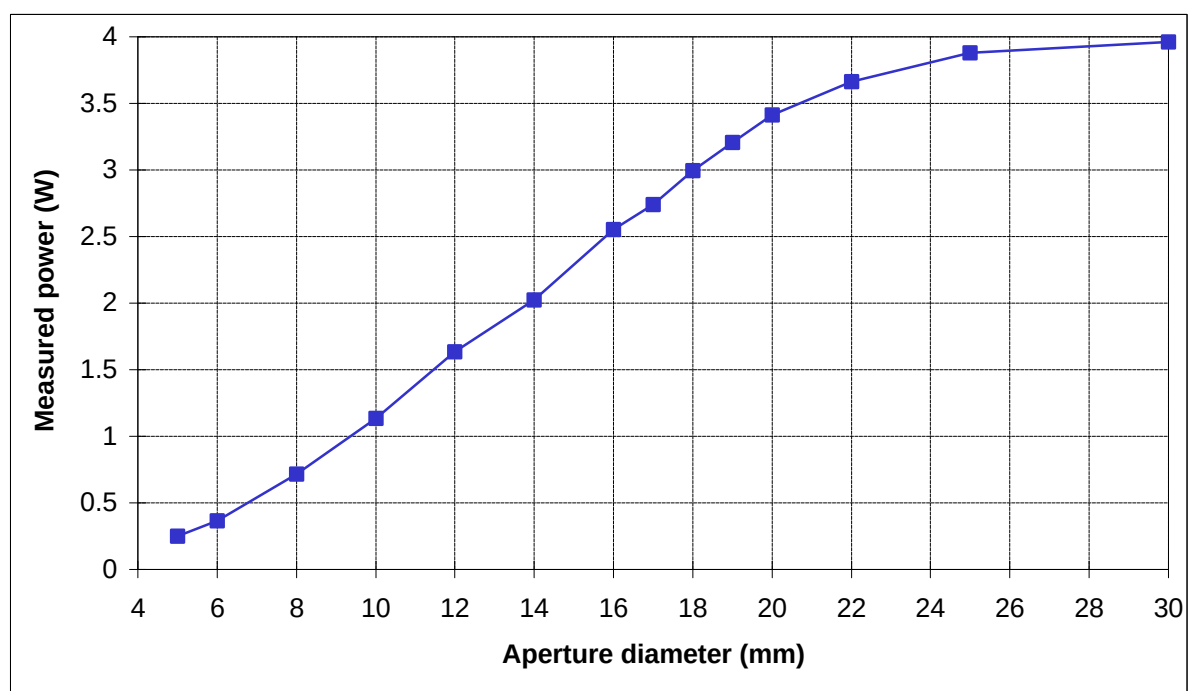


Figure 5.5: Measured power as a function of aperture diameter from a 1 MHz 25 mm diameter crystal Enraf transducer

The data shown in Figure 5.5 suggests that this particular device is a ‘well behaved’ transducer, and agrees well with data acquired using the separate aperture technique seen

in Figure 4.4. The acquired power data as a function of aperture diameter was analysed in a manner analogous to the techniques used to derive effective radiating area (A_{ER}) values from IEC 61689 beam plotting data described in detail previously (10). It is summarised briefly here. The difference in power values measured through successive aperture pairs is converted to an intensity contribution by dividing by the relevant annular area, and these intensity contributions are then sorted in descending order. They are then converted back to powers, and running sums of cumulative power and cumulative area are produced which may then be graphed.

For the data shown in Figure 5.5, the corresponding plot is shown in Figure 5.6. The curved blue trace is the running sum data, and the red horizontal line is the threshold value, corresponding to 75% of the ‘unapertured’ power. The value of the area which transmits 75% of the total power is simply read from the graph at the intersection of the two lines, and then divided by 0.75 to derive the effective radiating area. In this case, the effective radiating area of the transducer is 3.48 cm².

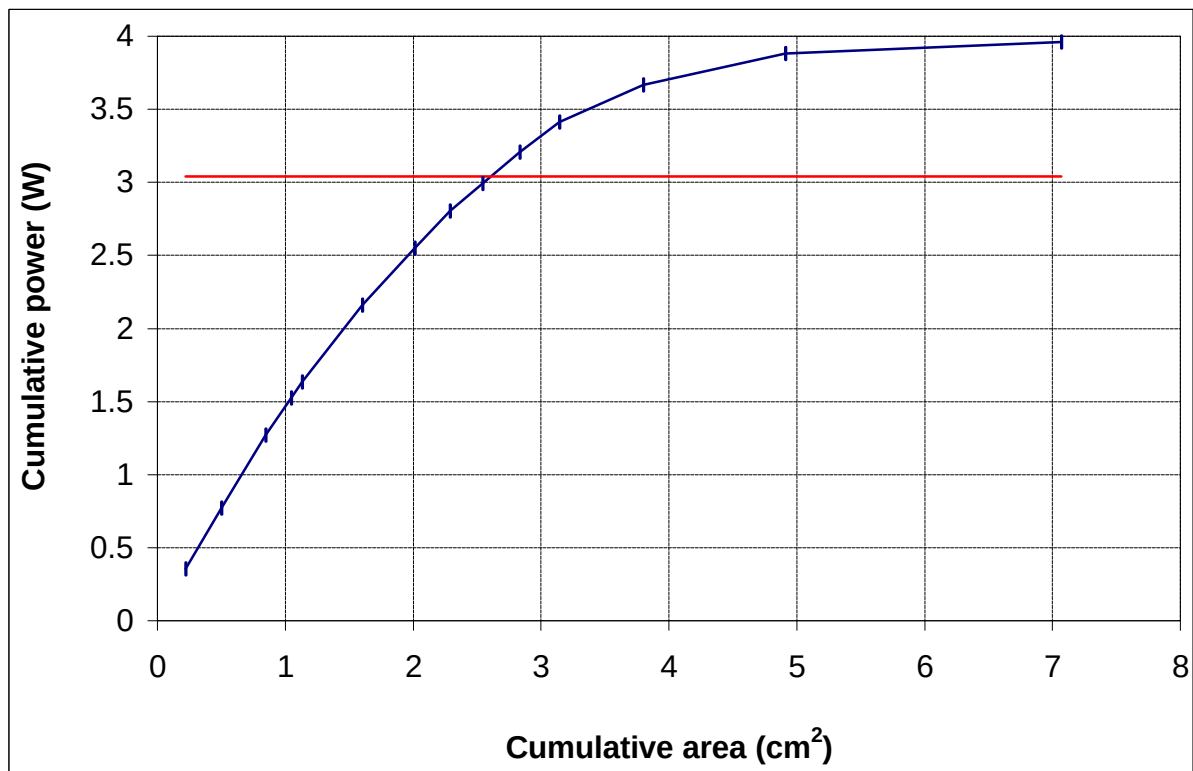


Figure 5.6: Cumulative power as a function of cumulative area derived from the data displayed in Figure 5.5

The data acquired for the 1 MHz large transducer case is considered to be of good quality, and was readily repeatable. The power values over the 4 OFF-ON-OFF switching cycles shown in Figure 5.4 show excellent reproducibility. As a result, the remaining power measurements on the three other reference transducers were performed using 2 OFF-ON-OFF switching cycles. In all cases, the data presented is a sample result – each transducer was characterised using TIPERAMS on at least three separate occasions, with agreement to better than $\pm 2\%$ seen between the different runs.

5.8.2.2 3 MHz large transducer

The plots of power as a function of aperture diameter and cumulative power against cumulative area are shown in Figures 5.7 and 5.8. The plot of power against aperture diameter is normalised to the unapertured power.

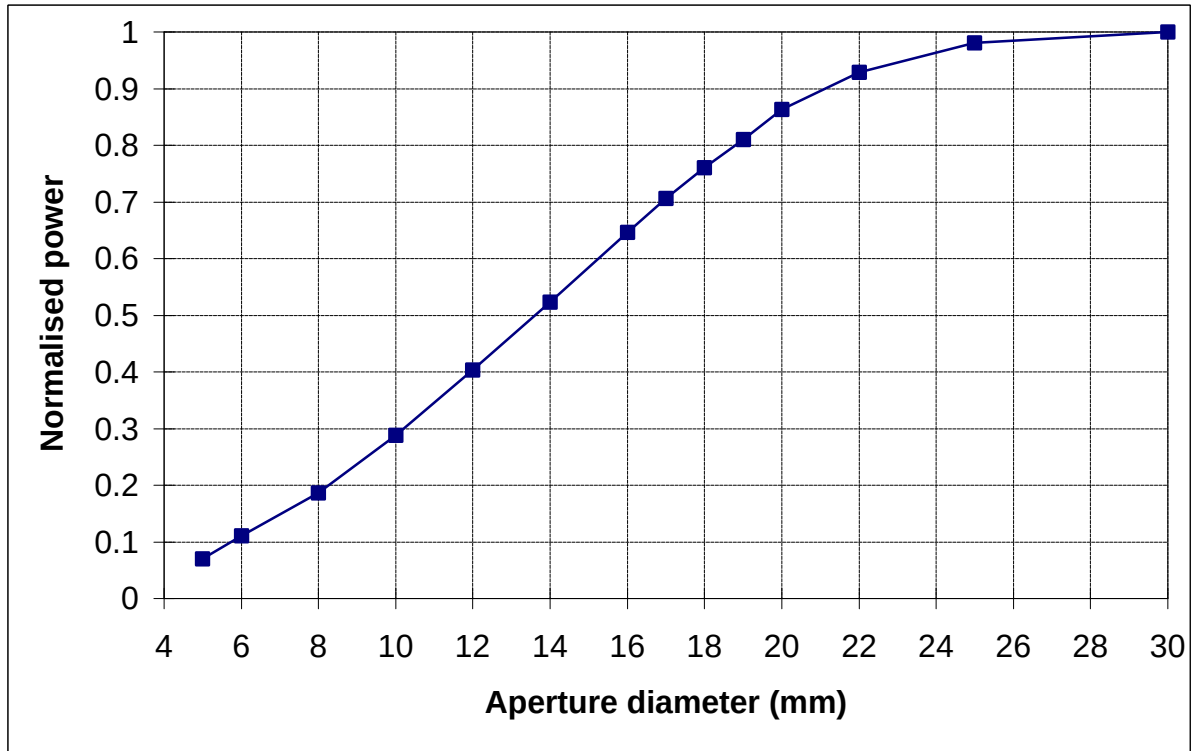


Figure 5.7: Normalised power as a function of aperture diameter from the 3 MHz 25 mm diameter crystal Enraf transducer

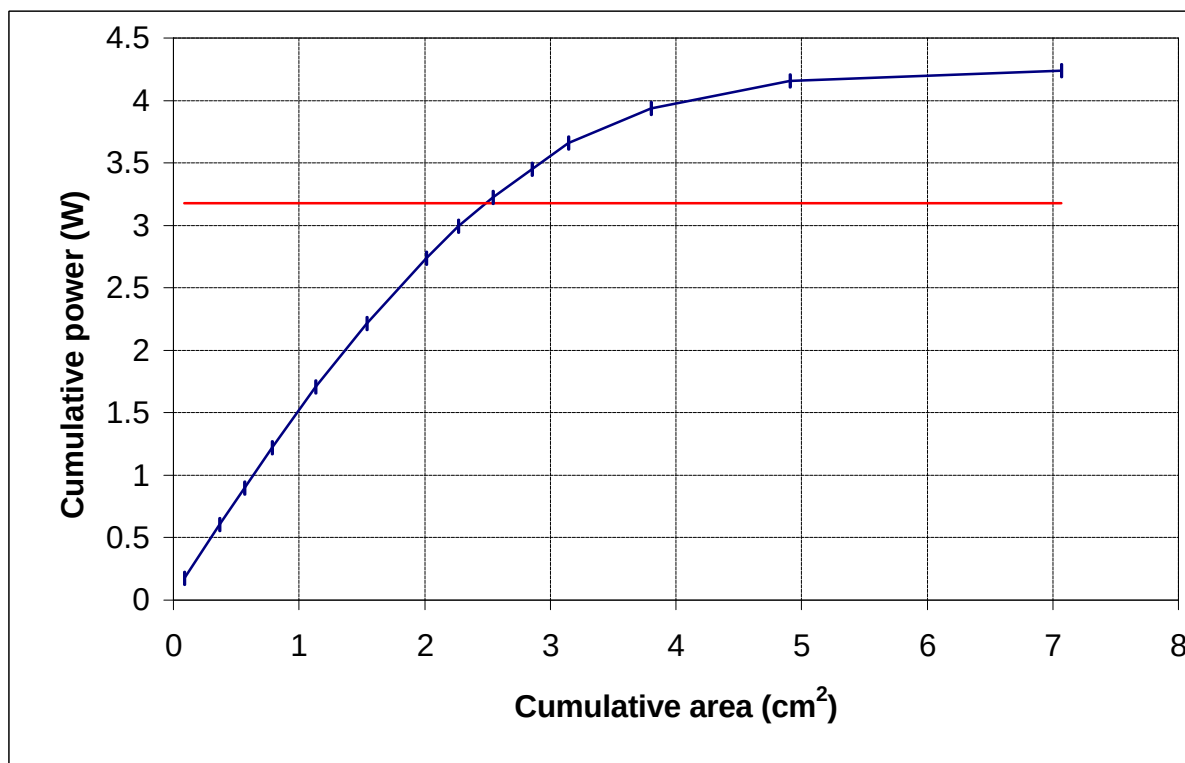


Figure 5.8: Cumulative power as a function of cumulative area derived from the data displayed in Figure 4.7

5.8.2.3 1 MHz small transducer

For the measurements on the two small transducers, the TIPERAMS system was changed so that the 'small' transducer wheel was used (aperture diameters in the range 4-18 mm). The plots of power as a function of aperture diameter and cumulative power against cumulative area are shown in Figures 5.9 and 5.10 respectively. The plot of power against aperture diameter is again normalised to the unapertured power.

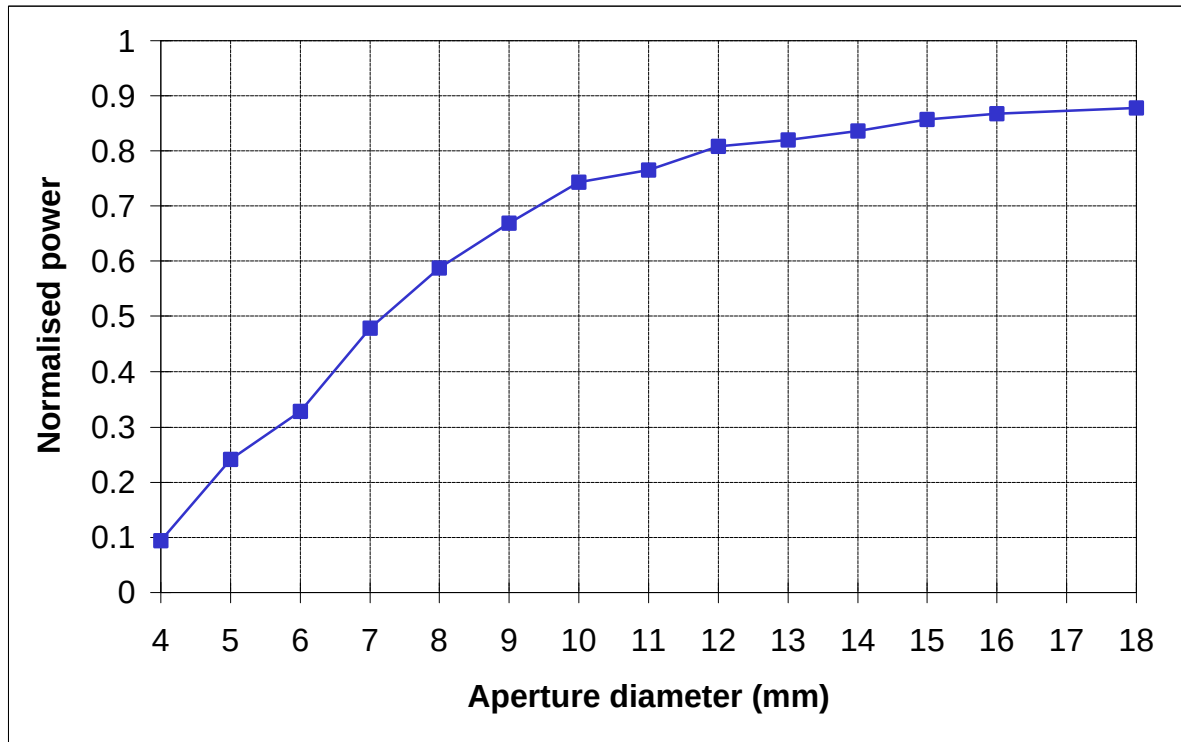


Figure 5.9: Normalised power as a function of aperture diameter from a 1 MHz 10 mm diameter crystal Enraf transducer

It is clear from Figure 5.9 that even with the 18 mm aperture in place, the transducer output is still less than 90% of the ‘unapertured’ power. This shows the significant divergence of the transducer beam. In fact, it has been seen previously (Figure 4.6) that even using a 30 mm aperture may not allow all of the transmitted power to impinge on the target. It is likely that the configuration is under-reading the power emitted by the aperture in each case. In terms of calculating a value for the A_{ER} , this can have a significant effect, because the power measured through the smaller apertures should be greater, and the sorting-by-intensity procedure would then produce a cumulative power against cumulative area plot that reaches the 75% level within the first few intensity contributions, which would be through smaller areas. The analysed data is seen in Figure 5.10. As an example of the extent of the effect of under-reading, if each measured power value is increased by 15%, such that cumulative power figure is equal to the unapertured power, the resulting A_{ER} value is 25% lower.

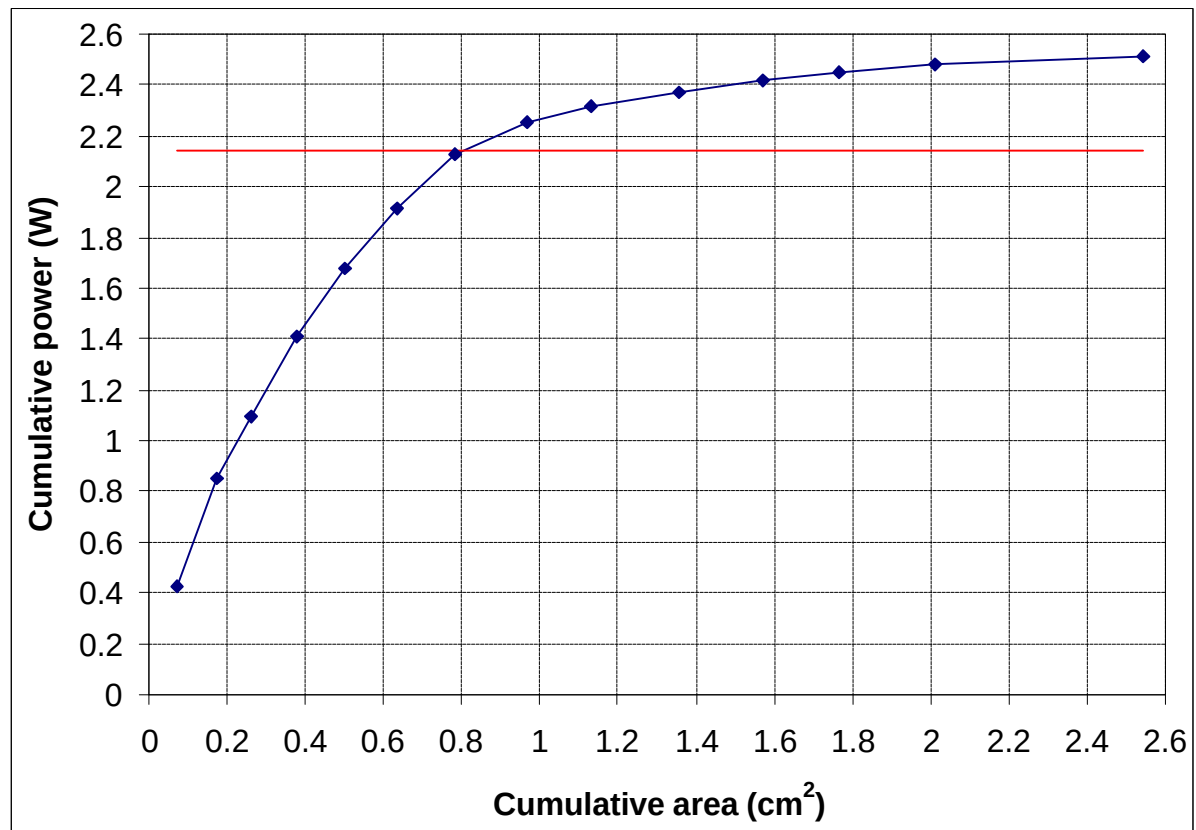


Figure 5.10: Cumulative power as a function of cumulative area derived from the data displayed in Figure 5.9

5.8.2.4 3 MHz small transducer

The plots of power as a function of aperture diameter and cumulative power against cumulative area are shown in Figures 5.11 and 5.12. The plot of power against aperture diameter is normalised to the unapertured power. By contrast to the small 1 MHz transducer data, the 3 MHz case actually ‘overshoots’ the unapertured power by 5%. The reasons for this are unclear, although it is possible that placing the aperture in front of the transducer produces some form of ‘waveguide’ effect, whereby the relatively long (15 mm) column formed by the absorber material and the backing plate serves to reflect the divergent incident ultrasound toward the target. This was investigated qualitatively by changing the separation of the transducer and the absorbing wheel, but no firm conclusions could be drawn. However, the effect on the A_{ER} value is small, because the cumulative plot reaches the 75% level between the third and fourth aperture-pair contribution – see Figure 5.12.

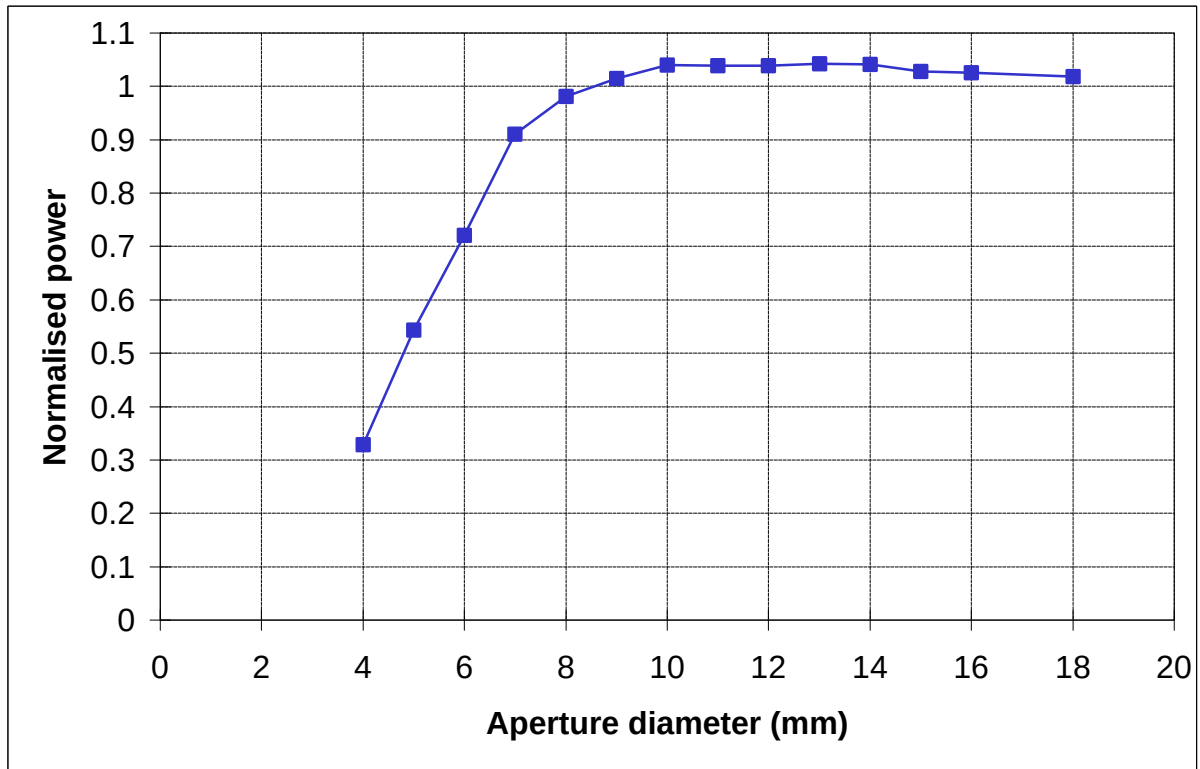


Figure 5.11: Normalised power as a function of aperture diameter from a 3 MHz 10 mm diameter crystal Enraf transducer

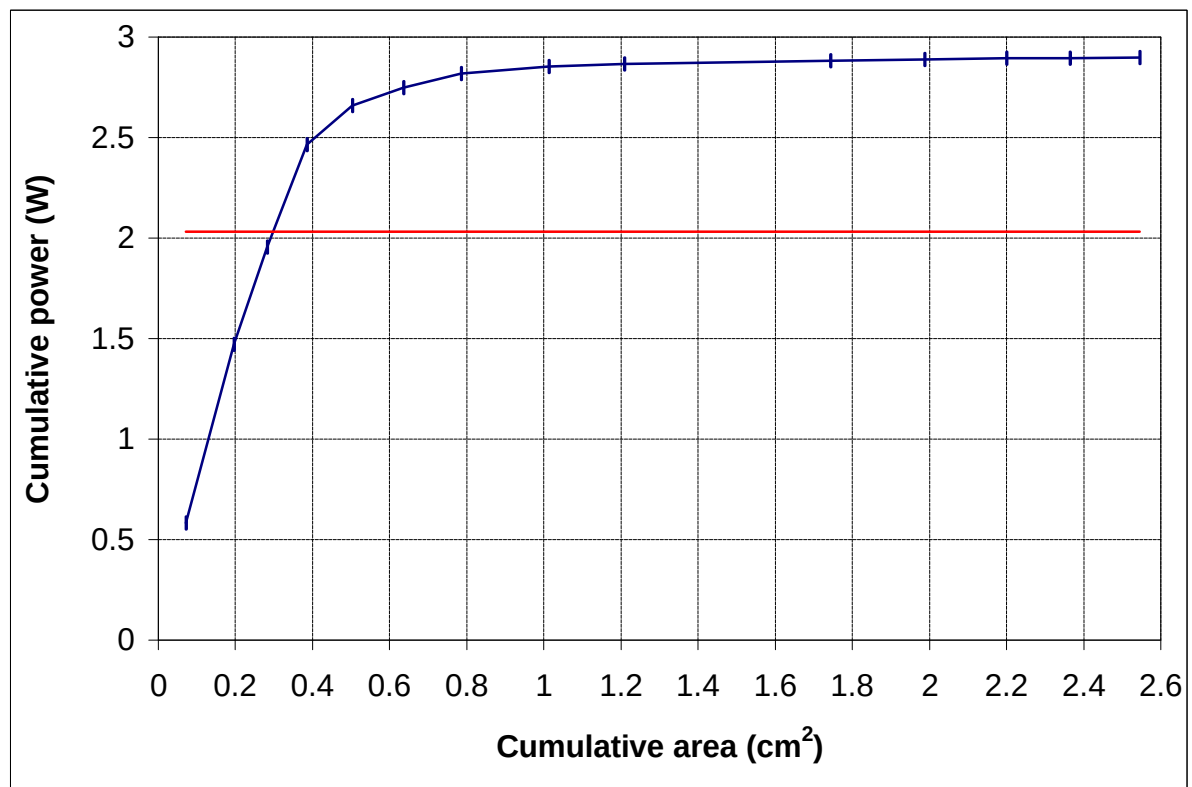


Figure 5.12: Cumulative power as a function of cumulative area derived from the data displayed in Figure 5.11

5.8.3 Discussion of reference testing results

The A_{ER} values derived from the measurements reported for the four reference transducers are listed in Table 5.1, alongside the data obtained from the IEC 61689 and target comparison work.

Table 5.1: Comparison of A_{ER} values, all techniques

Transducer	IEC 61689	IEC 61689, extra data	Hydrophone scan at output face	Adaptor and absorbing target	Adaptor and reflecting target	TIPERAMS
1 MHz large, 16.318	$3.44 \pm 9\%$	3.46	3.41	3.53	3.27	3.43
3 MHz large, 05.428	$3.46 \pm 10\%$	3.47	3.32	3.36	3.29	3.32
1 MHz small, 05.270	$0.85 \pm 17\%$	0.93	0.73	1.13	0.77	0.96
3 MHz small, 12.973	$0.37 \pm 20\%$	0.40	0.41	0.42	0.45	0.40

The table shows that for all but the 1 MHz small transducer, the TIPERAMS method produces A_{ER} data that agrees well with all of the other techniques studied. Considering the methods, it is to be expected that the TIPERAMS figure for the 1 MHz small transducer is of a similar order to the adaptor and absorbing target technique, as the experimental set up is similar. However, as commented above, the adaptor and absorbing target value was unexpectedly high, and so it is not appropriate to draw firm conclusions when considering that technique.

Considering the requirements of IEC 60601-2-5, which state that the A_{ER} must be determined to $\pm 20\%$, the TIPERAMS technique is within the limits when compared to the conventionally-derived IEC 61689 figure, even for the 1 MHz small transducer. As has been discussed previously however, there may be weaknesses in the accuracy of the IEC 61689 technique for small ka treatment heads anyway, with the linear regression analysis tending to underestimate the true A_{ER} value.

In summary, the TIPERAMS implementation of the aperture technique appears to produce accurate, good quality data. A typical full characterisation takes around 15 - 20 minutes to complete, which is an improvement of a factor of two over the previous discrete implementation. Such a full characterisation would only be required for acceptance testing or fault investigation purposes – periodic checks on a working treatment head could be restricted to checking the value given by 3 or 4 apertures, and comparing the results against the reference set. Such a task could be accomplished in around 5 minutes.

5.9 ANCILLARY INVESTIGATIONS

A series of additional studies were carried out to assess the significance of changing simple factors relating to the process. The majority of these contribute to the assessment of the overall uncertainty of the system in the determination of A_{ER} .

5.9.1 Wheel comparison

As discussed in Section 5.3.2, the decision was taken early on during the development phase to use two separate absorbing wheels, notionally applying to ‘large’ and ‘small’ transducers. To compare the performance of the two wheels where particular aperture diameters were duplicated, the 1 MHz large Enraf transducer was characterised using both wheels, with the output level of 4 W used for both cases. The results are shown in Figure 5.13.

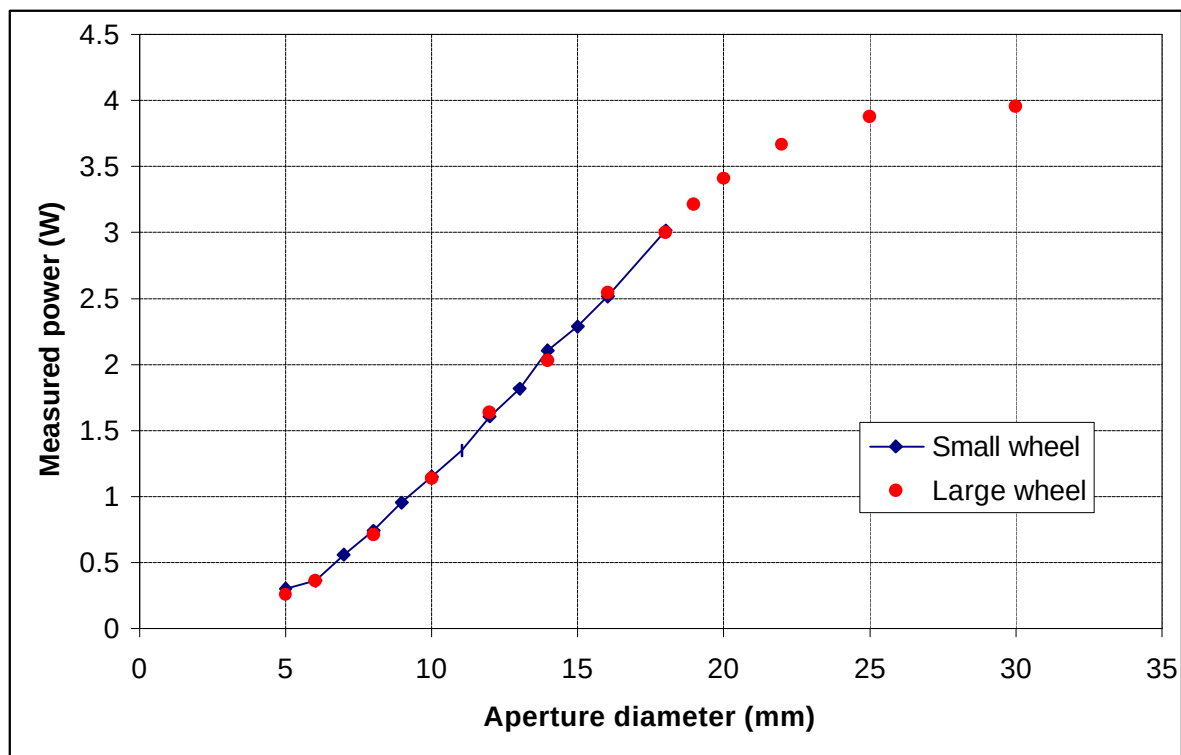


Figure 5.13: Comparison of power measured through application of large and small aperture wheels to the 1 MHz large Enraf transducer

The agreement between the average of the 5 unapertured measurements acquired for each wheel was $\pm 0.2\%$. Over the 8 duplicated aperture sizes, the agreement is generally 2% or better, although the worst case is for the 5 mm aperture, where the small wheel produces an 18% higher value. Such a large discrepancy was unexpected, and it was decided to investigate the 3 MHz large Enraf to provide an additional comparison. The acquired data is shown in Figure 5.14.

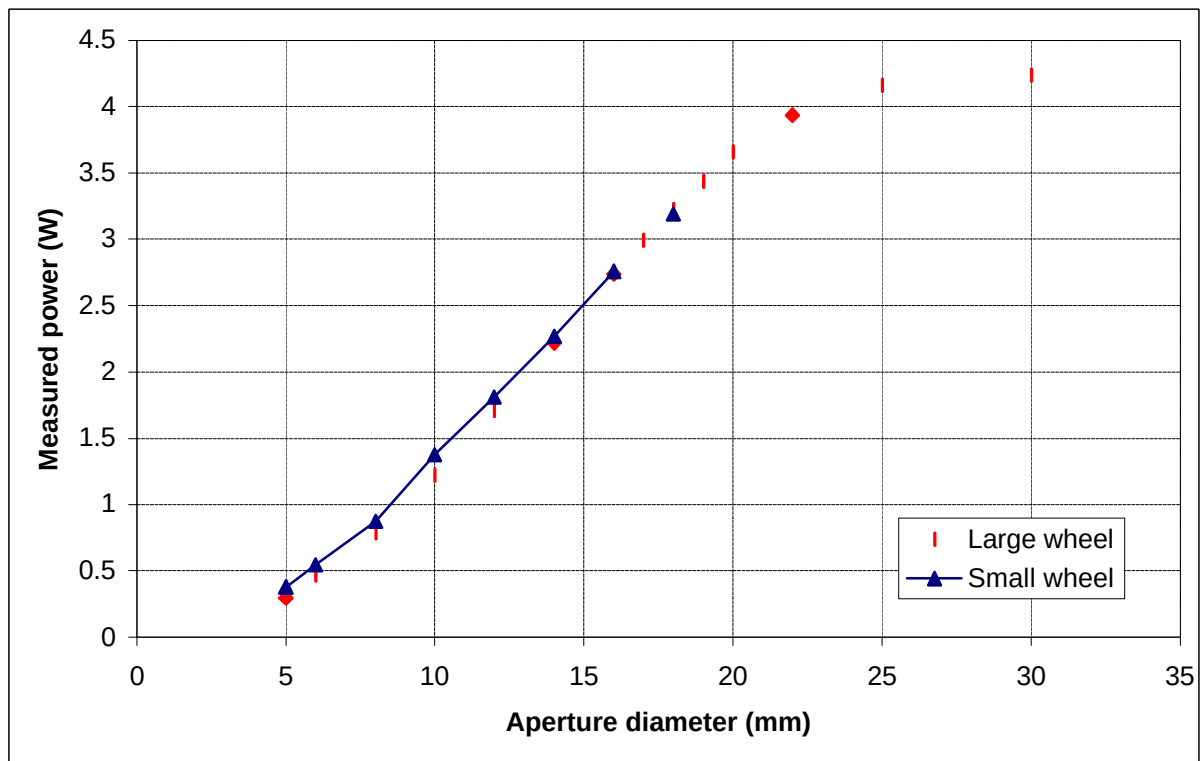


Figure 5.14: Comparison of power measured through application of large and small aperture wheels to the 3 MHz large Enraf transducer

For the 3 MHz case, the eight common aperture sizes showed some larger discrepancies than for the 1 MHz case, with the worst case values again at the smaller aperture sizes, and yielding values for the small wheel of up to 11% higher than the small wheel. On investigation of the two wheels, it was found that the large wheel had some errors in the positioning of the smaller diameter apertures. This was worst for the 5 mm aperture, of the order of 1 mm, and is almost certainly the reason for the small transducer wheel producing a higher transmitted powers for these cases. It is likely that the incorrect positioning arose during the aperture-cutting part of the production process. The error had an impact on the measurements because the initial alignment (from which all subsequent aperture measurements are made) was carried out using the larger aperture sizes as a datum.

Despite the sensitivity of the aperture technique at the smaller aperture diameters, this does not have a significant effect on the derived A_{ER} value – if the 3 MHz transducer large wheel data is re-analysed using the 5 mm aperture power obtained with the smaller wheel, the A_{ER} value is altered by only 1%. However, such an error has implications for the technique in terms of the manufacture and take-up – the processes used to form the apertures would need to be improved if the aperture method is to be robust and reproducible between different systems. This might also explain some of the difficulties seen when making measurements on the small transducers.

5.9.2 Variation of measured power with distance

5.9.2.1 1 MHz small transducer

With the small transducer aperture wheel in place, the system was lined up as normal, and the 40 mm diameter aperture located in front of the small 1 MHz Enraf transducer. Using a micrometer adjuster, the position of the transducer relative to the absorbing target was varied. The casing of the transducer allowed it to be lowered part way through the 40 mm diameter aperture and to a position almost touching the target, as depicted in Figure 5.15:

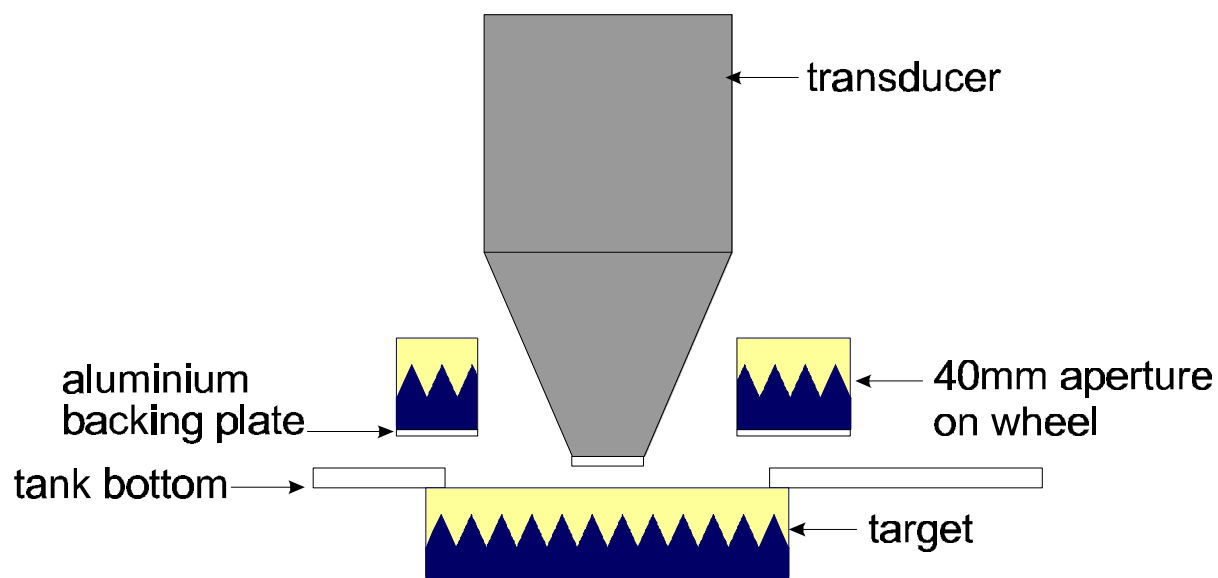


Figure 5.15: Schematic of experimental set up for distance variation measurements

The transducer crystal was aligned nominally over the centre of the target, and in the centre of the aperture, and measurements were then made of output power as a function of vertical position. The starting position was with the transducer crystal level with the tank bottom, and hence 3 mm away from the absorbing target. The resulting data is shown in Figure 5.16.

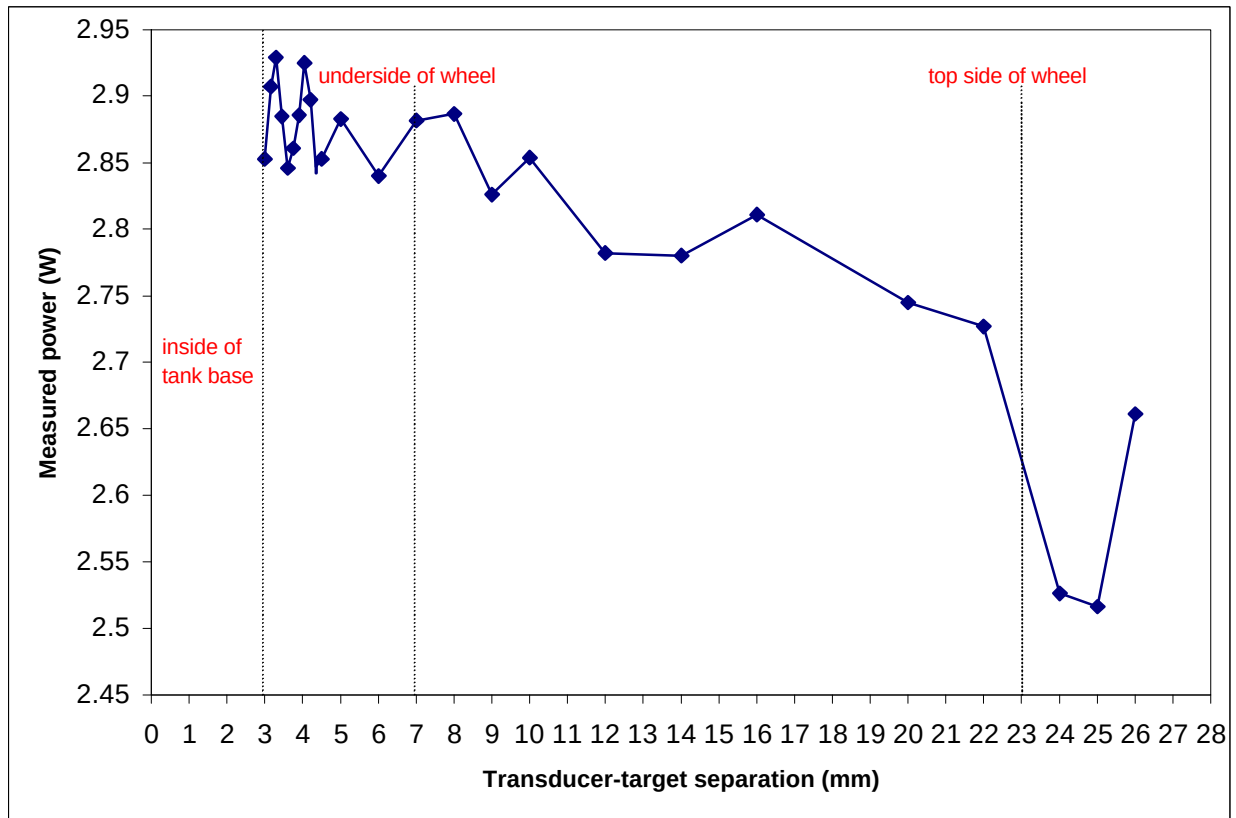


Figure 5.16: Variation of power measured through 40 mm aperture as a function of distance, 1 MHz small Enraf transducer. Note the expanded scale

The figure shows that there is a steady decrease in the measured power as the distance between the transducer and the target is increased, as expected. Certain features are marked on the plot, corresponding to structural elements in the experimental set-up. It is apparent that close to the target, a modulation in the measured power due to standing waves is seen – this is of the order of $\pm 3\%$. As the transducer is moved further up through the aperture, the power steadily decreases – this is probably due to a combination of the 40 mm aperture absorbing some of the incident ultrasound (due to the diverging beam), and the greater distance meaning that some of the emitted ultrasound misses the target.

As the transducer crystal approaches the top of the wheel, a sharp drop is seen in the measured power. The reason for this (repeatable) feature is not certain, but it is thought that the decrease in power is due to all of the emitted beam then being subjected to some attenuation by the aperture, rather than undergoing the ‘waveguiding’ effect described previously. The subsequent increase in power may then be due to a small displacement in the position of the wheel as more of the incident ultrasound is then absorbed: such a displacement in the position of the wheel would cause a slightly larger upthrust on the larger volume submerged (including the mounting pole), which in turn produces a small downwards force onto the balance pan.

The implication of this result is that for each aperture, including the nominal ‘unapertured’ measurement through the 40 mm diameter aperture, the true power is being underestimated, which was seen during the standard TIPERAMS characterisation for the 1 MHz small transducer (Figure 5.9). If the issue of target size against separation distance dominates the effect, the underestimate will be worst for the smallest aperture diameter

sizes. However, during normal measurements, the aperture-target distance remains fixed at nominally 5 mm, with the back side of the aperture wheel effectively forming the ‘emission surface’ in each case. Thus, the overall distance from the emission surface to the target is much smaller, and the overall effect on the power is probably less significant. Any underestimates in the true power will contribute to an overestimate in the A_{ER} value of the transducer.

5.9.2.2 1 MHz large transducer

A brief investigation was carried out of the variation in measured power for a change in vertical position for a transducer in the normal measurement location – approximately 2 mm from the wheel surface. The measurements were carried out over the 20 mm aperture, and are shown in Figure 5.17.

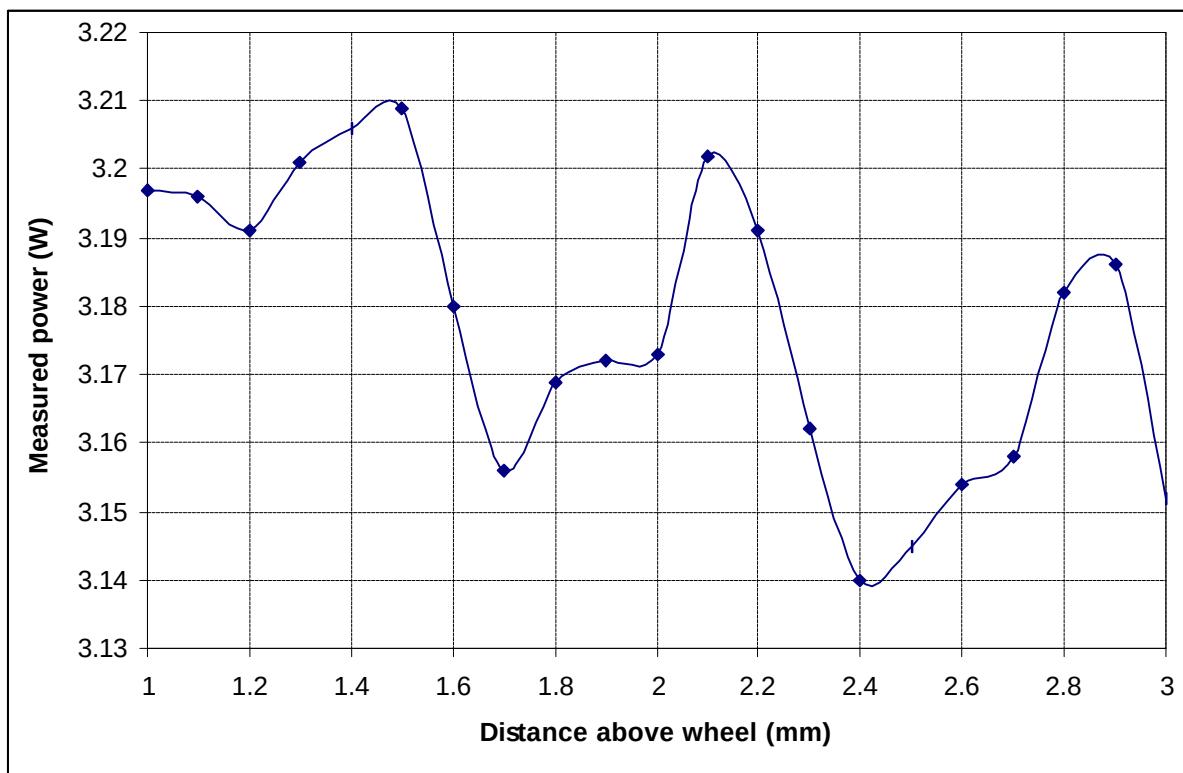


Figure 5.17: Variation in measured power with vertical position, 20 mm aperture. Again, note the expanded scale

The expected modulation is seen, with a peak-to-peak standing wave effect of around 2% observed – this is consistent with the echo reduction of the material at 1 MHz being 99%. In addition to the expected standing wave modulation, it is also clear that there is an additional feature which occurs immediately before the main modulation. However, this largely disappears when the radiation conductance plot is considered (Figure 5.18), and so may not be of significance. The findings from this investigation feed in to the uncertainty assessment (Section 5.11).

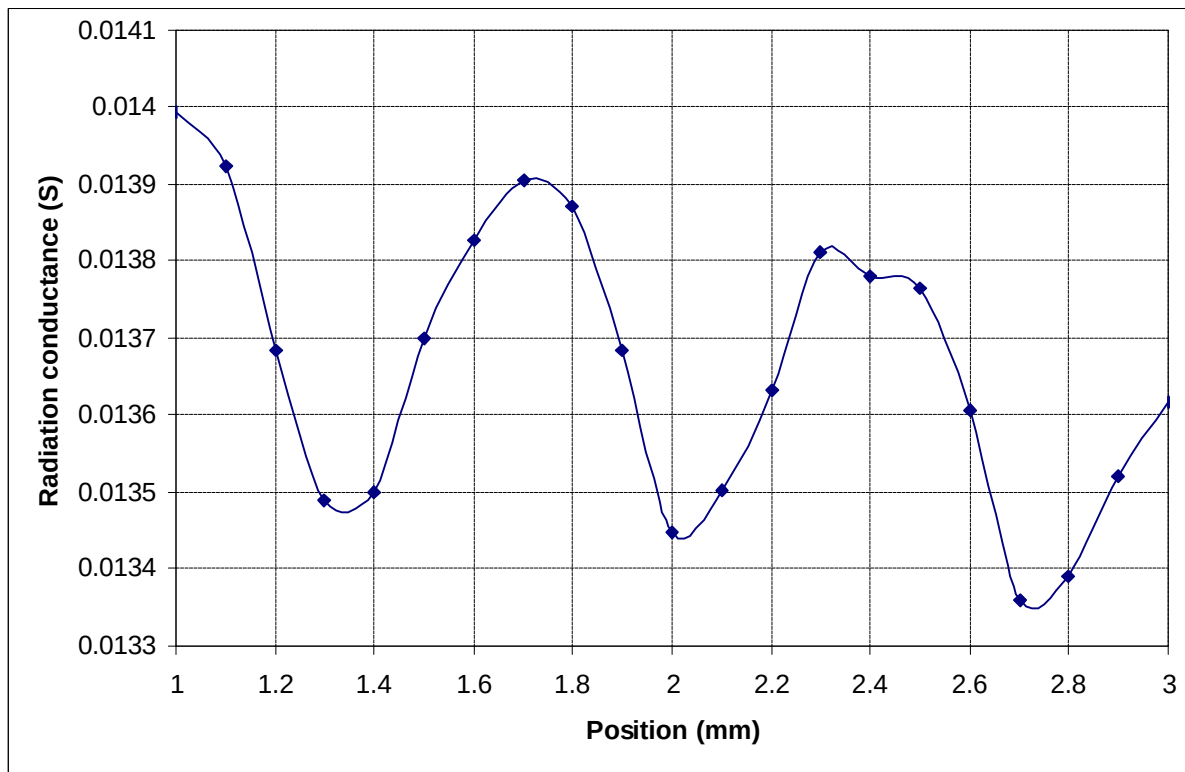


Figure 5.18: Variation in measured radiation conductance with vertical position, 20 mm aperture. Again, note the expanded scale

5.9.3 Investigation of incorrect positioning and alignment

It became clear during the testing phase for TIPERAMS that misaligning the transducer over the first aperture used could potentially cause significant errors in the value of A_{ER} measured, as the transducer is not re-positioned during the course of a measurement run. To test this, the 1 MHz large transducer was set up and carefully aligned, and a reference set of measurements carried out. Then, two other characterisation sets were performed with the transducer displaced by 1 mm and then 3 mm from the ‘carefully aligned’ position. Results are shown in Figure 5.19, as three normalised curves – in each case, the data points in a set are normalised to the unapertured power for that set. The three unapertured values (for the ‘0’, ‘1’ and ‘3’ cases) themselves agree to $\pm 0.2\%$.

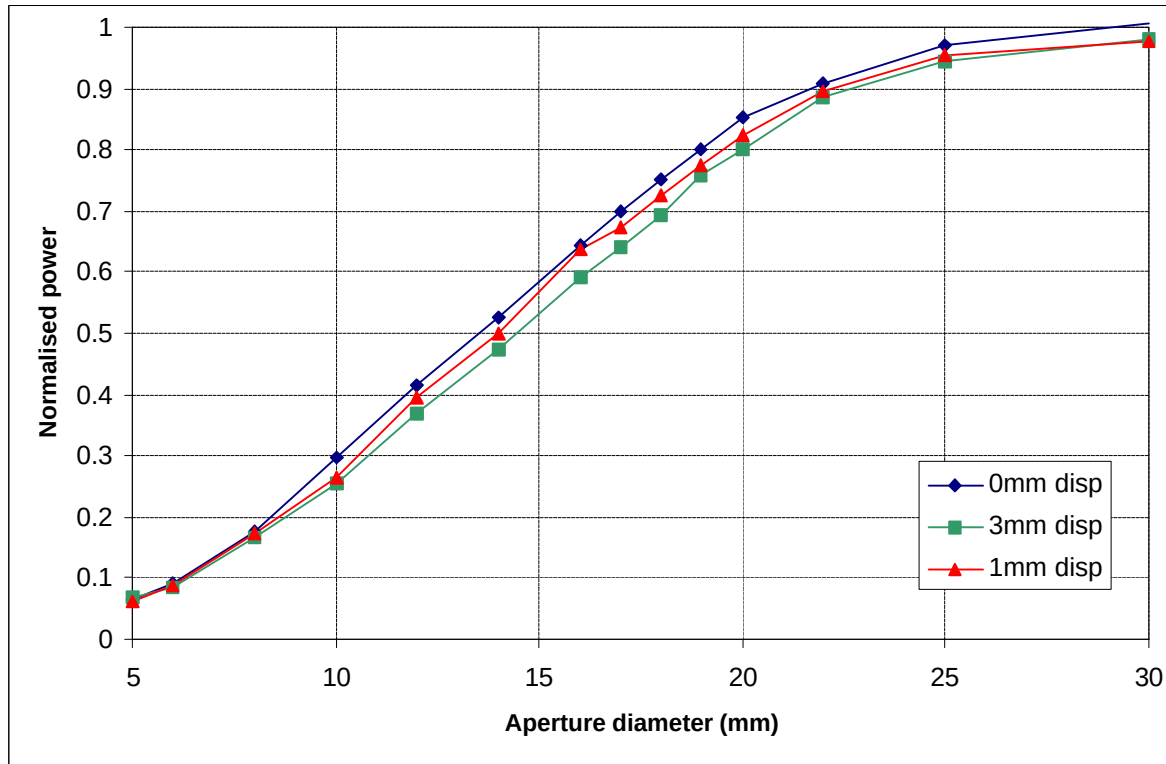


Figure 5.19: Comparison of three curves for the deliberately misaligned 1 MHz large transducer

The figure shows that the effect of the misalignment does not cause a significant underestimate of the power through the majority of the aperture – however, the effect on the A_{ER} value derived is more significant, as shown in Table 5.2:

Table 5.2: Comparison of A_{ER} values obtained from offset investigation

Displacement from ‘true’ position (mm)	0	1	3
A_{ER} (cm ²)	3.39	3.59	3.71

Again, the findings from this investigation feed into the uncertainty assessment.

5.10 CONSIDERATION OF CORRECTIONS FOR TIPERAMS VALUES

It is clear from Table 5.1 that there are significant differences between the A_{ER} values derived using the various techniques for the 1 MHz small transducer; the relevant line of the table is reproduced here:

Transducer	IEC 61689	IEC 61689, extra data	Hydrophone scan at output face	Adaptor and absorbing target	Adaptor and reflecting target	TIPERAMS
1 MHz small, 05.270	$0.85 \pm 17\%$	0.93	0.73	1.13	0.77	0.96

There is some uncertainty over the validity of the results obtained using the individual apertures and adaptors for this transducer (see Section 4.4), and so it is more appropriate to examine the differences between the TIPERAMS and beam plotting data. As discussed in Section 3.2, applying the IEC 61689 linear extrapolation technique to the A_{BCS} data obtained is perhaps not appropriate, because of the A_{BCS} values found from scans performed close to the output face.

It was commented there that a more appropriate analysis would be to simply take the value of A_{BCS} found close to the output face (at a transducer-hydrophone separation of 1 mm), and multiply this by 4/3 to calculate the A_{ER} value. Carrying this out for the 1 MHz small transducer produces the value of 0.73 cm² shown in the table. If this is taken as the true value of A_{ER} , a series of corrections to all of the TIPERAMS data can be evaluated, based on the differences seen between these two techniques. Such an approach produces the correction factors shown in Table 5.3.

Table 5.3: Empirically-derived TIPERAMS correction values

Transducer	IEC 61689	Hydrophone scan at output face	TIPERAMS	Correction factor
1 MHz large, 16.318	$3.44 \pm 9\%$	3.41	3.43	1.0059
3 MHz large, 05.428	$3.46 \pm 10\%$	3.32	3.32	1
1 MHz small, 05.270	$0.85 \pm 17\%$	0.73	0.96	1.315
3 MHz small, 12.973	$0.37 \pm 20\%$	0.41	0.40	0.98

For all but the small 1 MHz transducer, the corrections are very close to 1, which seems reasonable due to their higher ka values. To confirm the validity of this empirical approach, a range of small ka transducers should be evaluated using the two techniques, and the correction factors derived. These might then be compared with conversion factors produced by theoretical modelling, as discussed in Section 2.4.

5.11 UNCERTAINTY ASSESSMENT

Table 5.3 lists the sources and estimated values for the uncertainty in the accuracy of A_{ER} yielded by using the TIPERAMS system. These are considered for a single characterisation of a treatment head, rather than for repeats, and so a figure for repeatability is included – this is based on five characterisations of the 1 MHz large transducer, which yielded values of 3.38, 3.44, 3.48, 3.41 and 3.43 cm². This produces a standard uncertainty of $\pm 0.48\%$, which has then been doubled to provide a more realistic figure.

Table 5.3: Sources and values of uncertainty contributions

Source of uncertainty	Estimate of value (%)	Divisor	u_i (%)
Power measurement	± 2	1	± 2
Lateral positioning	± 3	$\sqrt{3}$	± 1.73
Vertical positioning	± 1	$\sqrt{3}$	± 0.577
Circularity of apertures	± 1.5	$\sqrt{3}$	± 0.866
Reproducibility of drive system	± 2	1	± 2
Finite target size	± 4	$\sqrt{3}$	± 2.3
Typical repeatability	± 1	1	± 1
Total			4.28
Expanded			8.6%

So, the uncertainty assessment suggests a figure of around 8-9% for the TIPERAMS technique. This is comparable to the figure derived for the uncertainty in beam plotting to derive values for A_{ER} according to IEC 61689, for the larger ka treatment heads.

5.12 SUMMARY AND CONCLUSIONS

The new implementation of the aperture technique, TIPERAMS, has been designed and realised successfully. A simple approach has been utilised for making power measurements, with an absorbing target attached to the water tank and the whole assembly placed on the pan of a 1 mg chemical balance. The apertures themselves have been realised using an enhanced formulation of the absorbing material initially employed, and a water jet cutting technique employed to produce the apertures. A simple data acquisition package has been used to provide balance time histories, which are then analysed using a second package to produce power data as required.

Four extensively-characterised reference transducers, all manufactured by Enraf, have been tested using the TIPERAMS system. A series of systematic studies has showed that the system produces A_{ER} values which compare very favourably with both reference IEC 61689 derivations, and with the previous discrete implementation of the aperture method, for both reflecting and absorbing target cases.

An assessment of the uncertainties in the values of A_{ER} produced by the TIPERAMS system has indicated that the system can determine A_{ER} to $\pm 9\%$, which is comparable to that achievable using hydrophone scanning techniques for larger ka transducers, and which represents an improvement over the uncertainties attained when characterising small ka heads to IEC 61689.

6 SUMMARY

The work undertaken in this project has covered a wide range of studies, which are discussed in their respective Sections. Some of the salient findings are summarised here:

- a finite-element (FE) model of the transducer-aperture-absorbing target configuration has been developed, which produces theoretical curves which show quite good agreement with experimental data, and will ultimately form the basis of a correction technique for the integrated system;
- four reference Enraf transducers have been characterised extensively against IEC 61689 criteria, and this has shown that the A_{ER} value derived for small ka transducers is subject to large uncertainties due to the nonlinear changes in A_{BCS} as a function of distance;
- measurements on different individual aperture configurations have been completed, and have illustrated significant differences between the measured powers and the resulting A_{ER} values determined using reflecting and absorbing target configurations, again especially for small ka transducers;

The most significant accomplishment of the project is the successful development of the integrated system for measuring power and determining A_{ER} , TIPERAMS:

- the new implementation utilises a wheel approach, which has significantly reduced the time taken to complete a measurement on a single physiotherapy transducer, such that reference power measurements and an assessment of effective radiating area can now be completed in approximately 20 minutes: subsequent checks carried out using a small number of apertures would then take 5 minutes or less;
- the acquisition and analysis of data is computer controlled, and the mechanics of the system have been designed such that automation of the stepping process is possible as a future refinement;
- for the reference transducers characterised, good agreement has been found between the TIPERAMS system, IEC 61689 reference techniques, and the use of the individual apertures with both reflecting and absorbing targets;
- the overall uncertainty of the TIPERAMS has been evaluated at around 9%, and this compares well with typical uncertainty values obtained using IEC 61689 criteria.

7 FURTHER WORK

To extend the validation of the TIPERAMS system, and to widen the acceptance of the aperture technique in the international arena, some suggestions for further work are listed:

- further validation on a wider range of transducers used in clinical practice – larger crystal areas, smaller ka values;
- the automation of the system to improve throughput;
- the production and submission of an amendment to IEC 61689, allowing the aperture method to be used as a complimentary technique (this work forms part of the 2001-2004 Acoustical Metrology Programme);
- refinement of the design to make the system more accessible to users and manufacturers, for example, by lightening some components such that a lower cost balance may be used;
- improvement of the existing wheel-changing mechanism, to improve the speed and durability of the system;
- investigation of the use of NPL's lower cost acoustical absorber to form the aperture wheel and evaluate the system performance;
- extension of the theoretical model to the full range of ka values, and development and validation of a full correction procedure, principally for smaller ka transducers.

8 ACKNOWLEDGEMENTS

The authors acknowledge the financial support of the National Measurement System Policy Unit, and the contribution of Wendy Brosnan in carrying out some of the measurements.

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