Practical Assessment of Phased Array Beam Generation

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Abstract: A recent study by MBEL has confirmed that the characteristics of the ultrasonic beams generated by a phased array probe can be significantly different to those specified by standard focal law calculators utilising geometric optics to determine the timing delay for each array element. A corrective term can be applied to the resulting generated beam angle producing satisfactory beam characteristics.
Further to this study some theoretical models and empirical laws have been developed and assessed. These showed similar behaviour thus validating the experimental values and the assumptions for each model. Unfortunately the model results do not map close enough to the experimental values to be used directly and the empirical laws determined can not be extrapolated to all cases.

Introduction

Phased array probes are more complicated than conventional probes, using many elements to generate a single beam. The beam characteristics can be modified by altering the firing sequence of the elements. A focal law is calculated to determine the firing sequence of the elements to generate a specific ultrasonic beam (number of active elements, beam angle and focal depth). Focal laws can be combined to produce a range of ultrasonic beams which can then be cycled through rapidly. As a result phased array probes can permit a faster and more precise inspection.

Testing has shown that the characteristics of the beam generated are not always as requested by the focal law. The angle measured is often different, and characteristics like the index point and wedge delay can also diverge from the values determined by a focal law calculation. As such we chose to study and understand the differences between the requested and generated ultrasonic beams from phased array probes.

Three phased array probes of differing frequencies were studied, 1 MHz, 2 MHz and 5MHz. Other differences between the probes included the pitch and the number of elements. Details are summarised in Table 1, Figure 1 illustrates the probe parameters.

The probes were used with active groupings of 8, 12 and 16 elements, generating unfocused beams with nominal angles of 30, 40, 50, 60 and 70 degrees without the use of wedges. This is a limited use of the capability of phased array probes; however more complex beam generation arrangements, such as an azimuthal beam sweep, are essentially a succession of such focal laws.

Assessment of the beam characteristics was performed using two different calibration blocks, Calibration block No.1, ref [1], (also termed an IIW block) and a bespoke calibration block labelled FR05. Illustrations are given in Figure 2 and Figure 3 respectively.

Name	Frequency (MHz)	Number of elements	Pitch (mm)	Inter-element space (mm)	Width (mm)
NPA 4834 A 101	1	24	2.5	0.5	15
NPA 4894 A 101	2	32	1.6	0.25	15
NPA 007	5	32	1.0	0.1	10

Table 1 : general characteristics of the probes

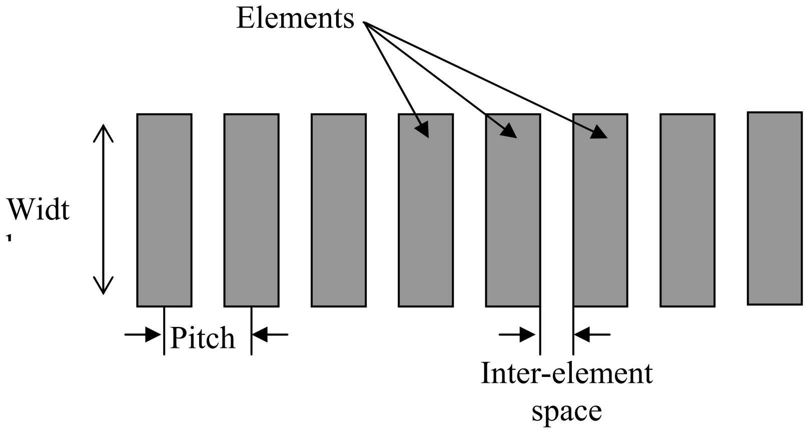


Figure 1: sketch of a phased array probe

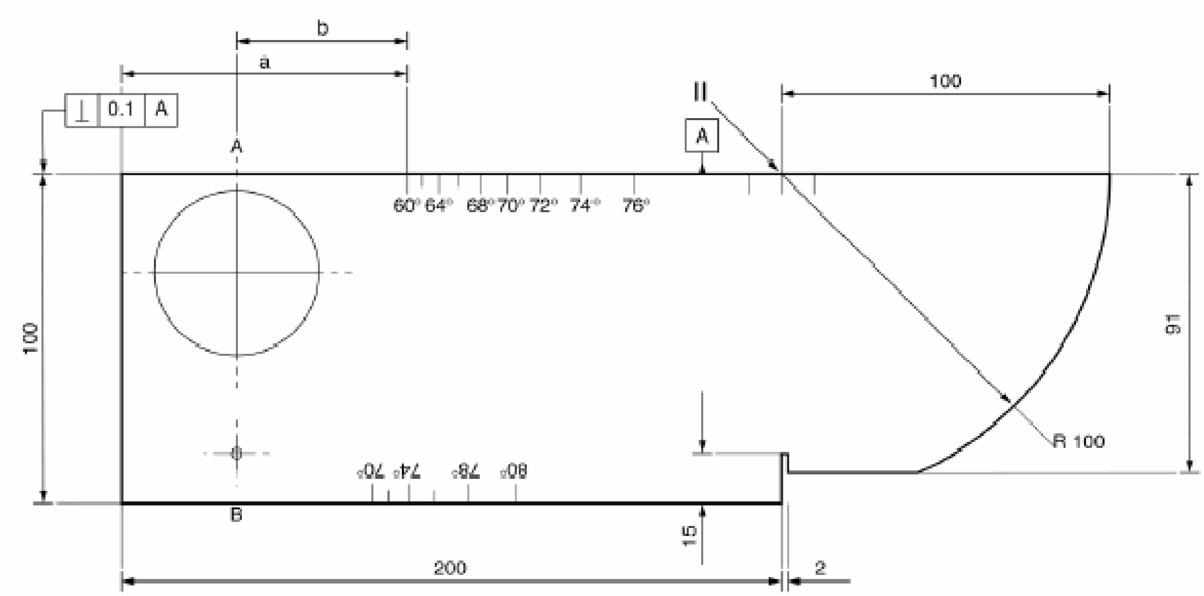


Figure 2: Calibration block No. 1

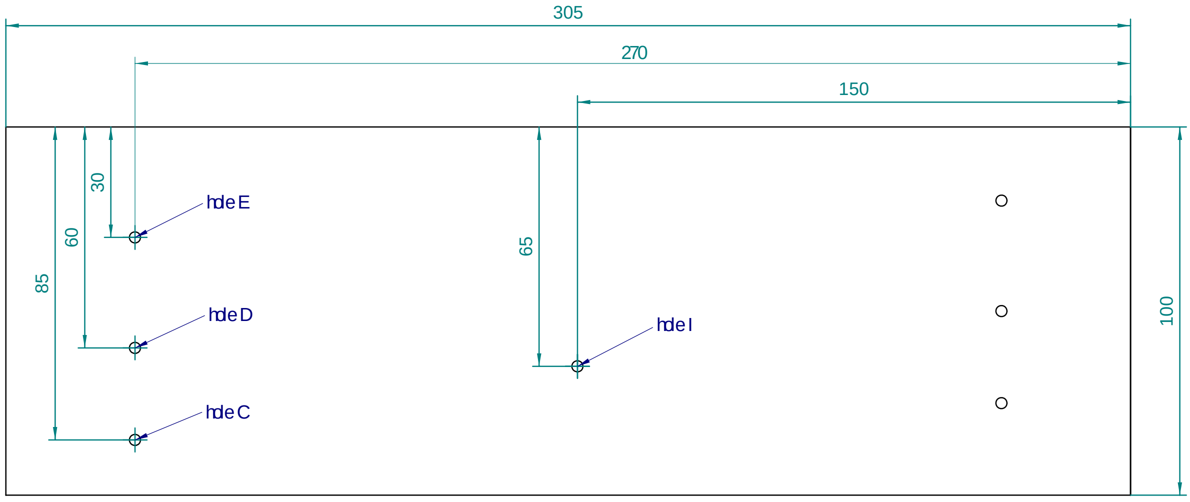


Figure 3: Calibration block (FR05)

Experimental Arrangements

Method 1: Evaluation of Beam Characteristics using Calibration block No.1

The index point and wedge delay were measured for each requested beam angle between 30 and 70 degrees, for the differing number of active elements (8, 12 and 16), for each probe from calibration block No.1. These values were subsequently used to measure the generated beam angles directly from the angular scale, see Figure 2.

The precision of this method is crude, nevertheless this technique is fast and representative of the calibration an operator would perform in the field when using a conventional probe.

Method 2: Capture of Data from block FR05

Another series of measurements were made using the calibration block FR05. The generated UT beams were set up to detect the holes I, E, D and C as defined Figure 3. The probe position was recorded using a linear encoder and the scan data captured for analysis afterwards. An illustration of the resulting image from the captured data is presented in Figure 4.

Using the captured data the position of the probe and the range to the maximum signal from each SDH were established. This information can then be used to plot a beam path and subsequently determine the beam angle, index point and wedge delay. This method was as reliable as the first method but the analysis is more complicated.

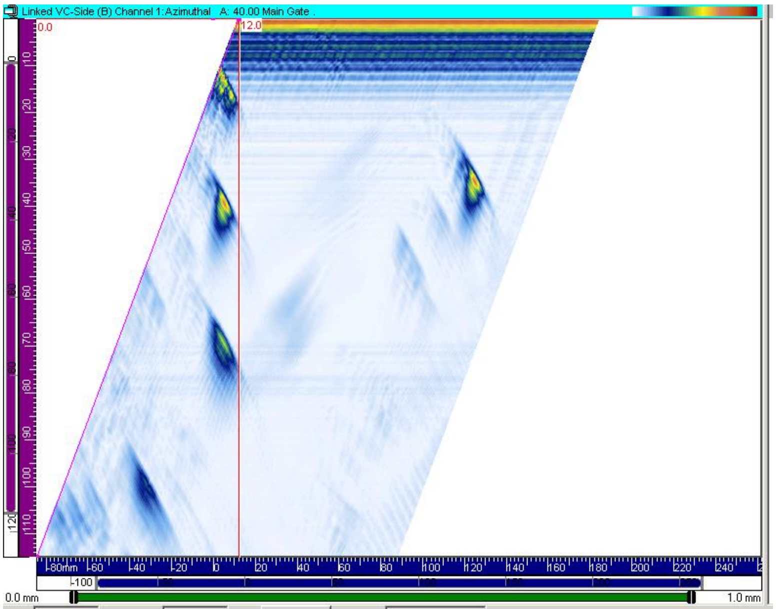


Figure 4 : B-Scan screenshot from the third series of experiments

Standards and Tolerances

As phased array probes are a relatively new application of technology for ultrasonic NDT, no standards for tolerance of beam behaviour exists as yet. Given that each generated beam from a phased array probe is similar to that of a conventional probe, the tolerance standards from BS-EN 12668 for conventional probes, ref [2], was considered suitable for the analysis of the data. Mitsui Babcock had done some previous work on this area, ref [3], and RD Tech have published details in their books on phased array, ref [4] and ref [5]. From this some practical tolerances can be established for phased array applications as shown in Table 2.
The tolerance value for the wedge delay was inferred from the depth tolerance values in Table 2. An error in the wedge delay value can appear as an error in the depth assessment of a signal. The tolerance accepted is defined as a percentage of signal depth, whereas the effect of a wedge delay error does not depend on the depth of an echo response. Thus the percentage of error due to the wedge delay is completely different if echo responses at differing depths are considered. As a result we chose to define a tolerance value resulting in a maximum error in depth of ±2mm. This will result in differing tolerances for the wedge delay for differing generated beam angles as detailed in Table 3.

Experimental Results:

It was impossible to obtain clear information about any of the 70° beams since the noise levels were excessive. A similar problem was noted for the 5MHz probe when generating beams of angles 60° and greater. It was thus concluded that for the phased array probe arrangements assessed these beams could not be satisfactorily generated.

From the extensive series of experiments performed, significant data relating to the wedge delay, index point and beam angle have been determined.

The results of the scans on block FR05 were analysed to check that the values of beam angle, index point and wedge delay were similar for each SDH and were then compared with the values determined by the focal law calculator. Further analysis was conducted looking at the results from arrangements with similar characteristics (i.e.: same probe, same number of activated elements but differing angle or same angle but different probe and number of elements). A first aim of this analysis was to determine if there was some abnormal behaviour, and a second aim was to deduce general behaviour characteristics and any empirical law(s).

It was noted that there was a change in the performance of the ultrasonic beams in practice at the differing depths of the SDH's within block FR05. A useful approach was to evaluate the maximum difference between each value determined from each SDH of calibration block FR05 and the associated values determined from calibration block No.1 and defined by the focal law. The aim was to determine the values of index point, wedge delay and beam angle of the various probe configurations and to obtain evidence of the level of deviation, if any, between beams generated in practice and the values predicted by a focal law calculator. The comparison of the results obtained from the A2 characterisation block are favourable and could allow the use of this approach as a simplified characterisation method for field work.

From these evaluations Table 4 was produced summarising the operating restrictions for the array probes assessed. In some cases, the results found for holes located close to the block's surface were consistent but diverged slightly from the general values determined. These probes can be utilised at these shallow depths providing they are fully characterised.

Beam angle	Beam angle tolerance			Hole depth tolerance (% hole depth)		Index point tolerance (mm)		
	BS-EN 12668		RD Tech			BS-EN 12668		RD Tech
	≤ 2 MHz	> 2 MHz	all	≤ 2 MHz	> 2 MHz	≤ 2 MHz	> 2 MHz	all
30°	± 3°	± 2°	± 2°	± 3%	± 2%	± 2	± 1	± 2
40°	± 3°	± 2°	±2°	± 4%	± 3%	± 2	± 1	± 2
50°	± 3°	± 2°	± 2°	± 6%	± 4%	± 2	± 1	± 2
60°	± 3°	± 2°	± 2°	± 8%	± 6%	± 2	± 1	± 2

Table 2 : UT beam tolerance value according to Standard BS-EN 12668 and RD Tech

Angle (degree)	1 MHz probe hole depth tolerance (mm)	1 MHz probe wedge delay tolerance (µs)	2 MHz probe hole depth tolerance (mm)	2 MHz probe wedge delay tolerance (µs)	5 MHz probe hole depth tolerance (mm)	5 MHz probe wedge delay tolerance (µs)
30	2.0	0.8	2.0	0.8	2.0	0.8
40	2.0	0.9	2.0	0.9	2.0	0.9
50	2.0	1.1	2.0	1.1	2.0	1.1
60	2.0	1.4	2.0	1.4	2.0	1.4

Table 3 : hole's depth and associated wedge delay tolerances

Modelling:

The performance of two models based on wave theory was compared with the experimental values. The aim was to try to explain the differences between focal law calculations and practical evaluation of phased array beam performance, and to determine if an alternative model could provide the values required for practical use of phased array probes, in particular for the evaluation of the beam angle.

First model   Fraunhofer approximation

The Fraunhofer approximation is a calculation valid in the far field and for angles close to the beam angle intended to be generated. This was not generally the case for our study or for field work; however some experiments have shown that this approximation can be valid from a practical viewpoint even when these conditions are not valid.

The Fraunhofer approximation is a way to calculate the wave's amplitude by looking with an angle β at a beam generated with a supposed angle β_0 by a phased array probe with:

- c = probe pitch between elements
- s = probe's inter-element space
- k = probe's wave number (given by $k = 2\pi/\lambda$ where λ = the beam's wavelength)
- N = number of elements activated

Probe	Elements	Angle			
		30	40	50	60
1 MHz	8	(> 60 mm) bad	(> 60 mm) bad	(> 60 mm) bad	
	12	(> 60 mm) correct	(> 60 mm) correct	(> 60 mm) bad	(> 60 mm) bad
	16	> 40 mm (60) correct	> 40 mm (60) correct	> 40 mm (60) correct	> 40 mm (60) correct
2 MHz	8	(> 50 mm) good	(> 50 mm) good	(> 50 mm) good	
	12	good	good	good	good
	16	> 40 mm good	> 40 mm good	> 40 mm good	> 40 mm good
5 MHz	8	excellent	excellent	excellent	
	12	excellent	excellent	excellent	
	16	> 60 mm excellent	> 60 mm excellent		

Comments refer to the quality of the generated signal

Values quoted refer to a range of operation for the probe arrangement

Values quoted in brackets (…) refer to a range of operation for the probe arrangement that can be used with caution

Key

Can be used

Not advised to use

Do not use

Table 4 : summary of the valid probes' configurations

The Fraunhofer calculation is given by the formulas:

$$u_{PA}(\beta) := \frac{(c - s)\cdot\kappa}{2}\cdot\sin(\beta)$$

u_{PA} is the diffraction factor

$$v_{PA}(\beta_0,\beta) := c\cdot\frac{\kappa}{2}\cdot\left(\sin(\beta) - \sin(\beta_0)\right)$$

v_{PA} is the interference factor

$$A_F(\beta_0,\beta) := \left(\frac{\sin(u_{PA}(\beta))}{u_{PA}(\beta)}\right)^2\cdot\left(\frac{\sin(N\cdot v_{PA}(\beta_0,\beta))}{N\cdot\sin(v_{PA}(\beta_0,\beta))}\right)^2\cdot\cos(\beta)^2$$

A_F = amplitude of the signal

This gives a beam shape similar to the one illustrated in Figure 5, the beam direction being the direction in which the wave's amplitude is the highest. A MathCAD worksheet was created to calculate the beam angle as a function of the probe parameters.

It is essential to notice that with the Fraunhofer approximation, the amplitude of the beam – and thus its angle – does not depend on the distance from the probe.

Second Model Kirchhoff calculation

The Kirchhoff evaluation is a simple "brute force" integration over each element. A major difference from the Fraunhofer model is that the amplitude of the wave depends not only on the angle considered but also on the distance between the probe and the point of interest. The calculation is not described here as only the result is of interest in this study, but further detail are contained in Physics of Waves by Elmore and Heald, ref [6].

An example of the amplitude of the beam for all the points of a surface parallel to the probe representative of a B-scan slice through the beam is given in Figure 6.

In same manner as with the Fraunhofer approximation, it is possible to calculate the values of the angle for which the wave amplitude is highest. Using this, the beam angle is calculated for the various probe parameters and for each SDH of calibration block FR05.

Assessment of Modelling Results

The Fraunhofer model has been compared in detail against the values of beam angle determined from calibration block No.1 and the values predicted by the delay law. This comparison shows that generally the measured angle and the Fraunhofer predictions are closer in value and lower than those specified by the delay law. However for low angles of around 30° the measured angle is greater than the delay law and the Fraunhofer model always predicts lower values. An illustration of these findings is given in Figure 7.

It seems possible that the near field structure of the beam may have a greater effect at 30° than at the higher beam angles and that this may account for this difference in performance between the measured beam angles and the Fraunhofer model.

Some preliminary comparison of the Kirchhoff model with the measured results from the FR05 block illustrates some correlation. However a detailed evaluation of the Kirchhoff model is presently ongoing, the findings and conclusions of this work will be reported elsewhere.

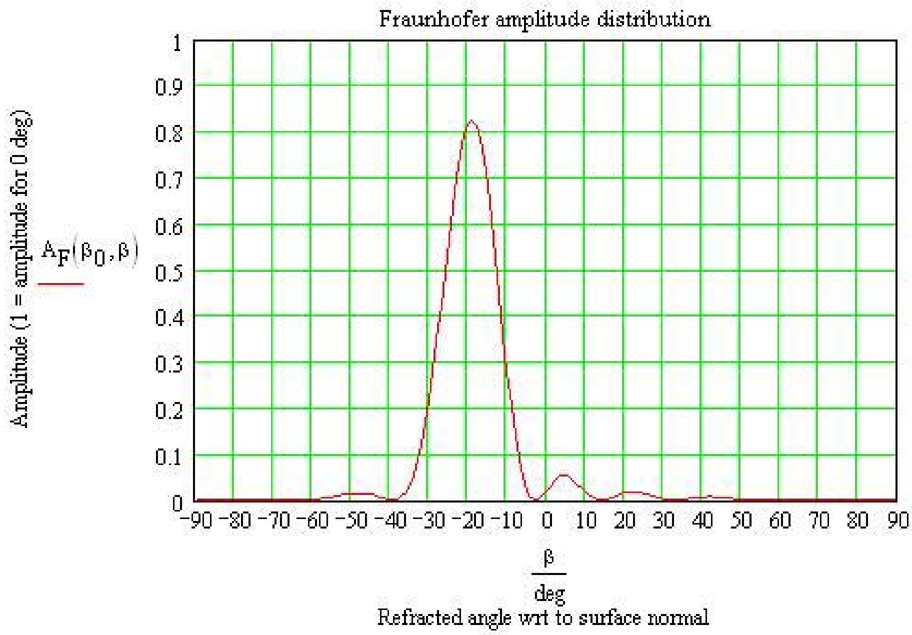


Figure 5 : beam amplitude curve for an angle of 20°

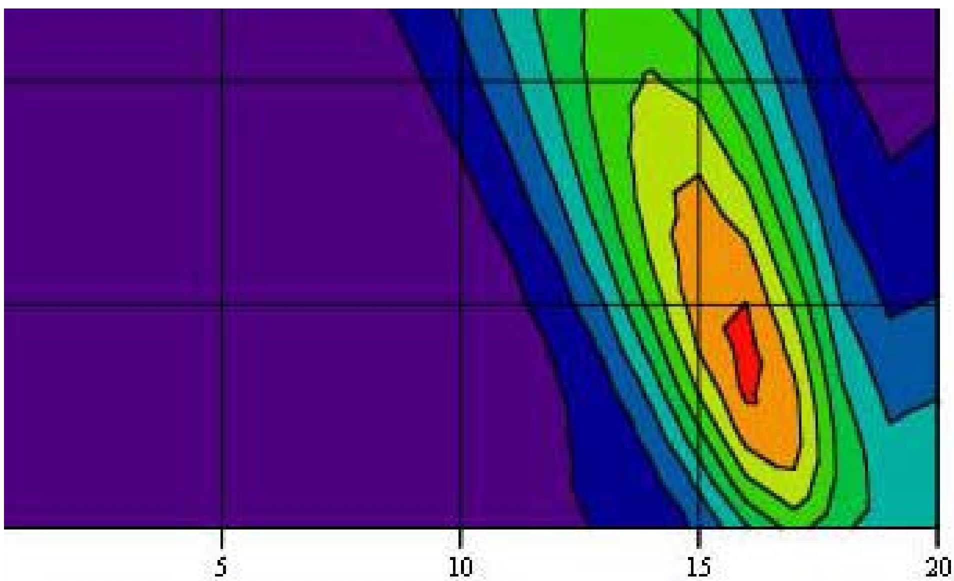
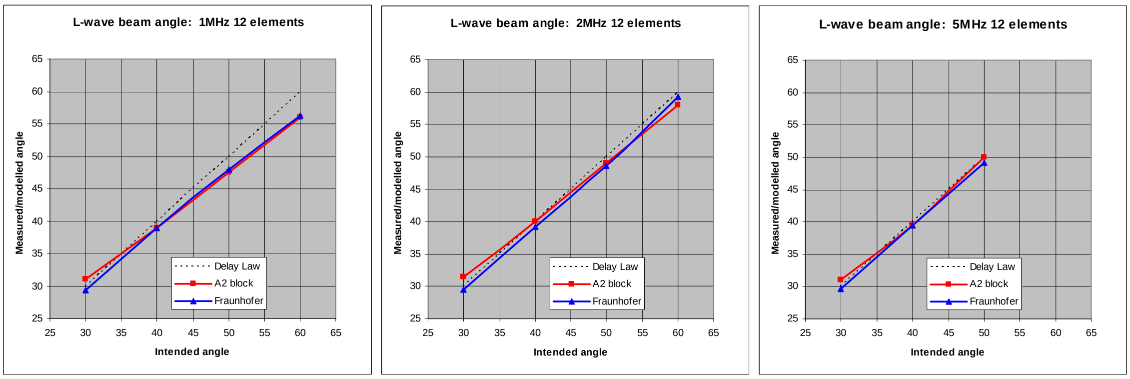


Figure 6 : B-scan amplitude of the signal as a function of the position



Note: A2 block is equivalent to Calibration block No. 1

Figure 7 Illustration of predicted beam angles for Fraunhofer model and delay law calculation and measured angles from calibration block No.1

Conclusions

This study has confirmed that the characteristics of the ultrasonic beams generated by a phased array probe are sometimes quite different from that requested. The wedge delay, index point and beam angle values determined can be out with the tolerance limits appropriate to conventional ultrasonic probes. Nevertheless the results are not completely inconsistent and this study has provided useful information.

The values determined from the two calibration blocks (Calibration block No.1 and FR05) correlate in the majority of cases, a corrective term is required for the beam angle in some situations. The correlation between the results gives evidence that a fast calibration method can be achieved for phased array probe applications.

Broadly speaking, the behaviour of the three analysed parameters is similar to the theoretical results from the Fraunhofer and Kirchhoff models. This confirms the validity of the measured values and the impact of the phenomena taken into account by the models. Unfortunately the theoretical models do not at present provide results close enough to the measured values to be used directly to determine the values of wedge delay, index point or beam angle for application. It may be possible to extend the theoretical models to create an advanced model capable of determining more accurately the behaviour of phased array applications.

Finally the coherence of the experimental results provides evidence that an extrapolation of the wedge delay, index point and beam angle can be achieved on a “local” scale. This could be useful to provide a selected and rapid assessment of multiple generated focal laws (e.g. assessing every 10° of an extended azimuthal scan or first and last law of electronic linear scan).

Acknowledgements

The majority of the practical and reporting work for this paper was carried out by Mr Damien Levecque during an industrial placement with Mitsui Babcock from July to September 2005. Mr Levecque is a student at the Ecole des Mines de Paris.

References

[1] British Standards Institution, “BS EN 12223, 2000, Non-destructive Testing- Ultrasonic Examination– Specification for Calibration Block No.1”, British Standards Institution, March 2000.

[2] British Standards Institution, “BS EN 12668-2, 2001, Non-destructive Testing- Characterisation of Ultrasonic Examination Equipment – Part 2, Probes”, British Standards Institution, May 2001.

[3] N B Cameron, “Phased Array Probes and Wedge Characterisation and Acceptance Criteria”, 3rd EPRI Phased Array Ultrasound Seminar, Seattle, USA, EPRI, June 2003.

[4] “Introduction to Phased Array Ultrasonic Technology Applications”, RD TECH, August 2004

[5] “Phased Array Technical Guidelines, Useful Formulas, Graphs and Examples”, RD Tech, May 2005.

[6] Elmore, W C & Heald, M A, “Physics of Waves”, Dover Publications Inc., 1985, New York.