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# Time efficient auto-focussing algorithms for ultrasonic inspection of dual-layered media using Full Matrix Capture

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ABSTRACT

This paper describesa number ofmethods for calculating the point of incidence at a planarrefractive interface between dual-layered media for ultrasonic applications in the field of non-destructive testing. It is shown how Snell's law may be expressed as a quartic polynomial, and solved using analytical or numerical techniques to find the point of incidence at the refractive interface. An array transducer mounted onto a Perspex wedge is used to generate ultrasonic imagery of a double 'v' butt weld in a low carbon steel plate, using the Full Matrix Capture technique. Curve-fitting algorithms are also presented that allowautomated focussingthrough the wedge-plate interface. Finally, a description is given on how algorithms may be adapted to allow auto-focussing through dual media with a non-planar interface.


## 1. Introduction

The use of linear array transducers in the field of ultrasonic non-destructive testing and evaluation (NDE) has become common place in recent years. Typically, elements in an array are excited in parallel to generate interference patterns in a component. By phasing the relative transmission times of individual elements, focussing and beam steering can be achieved, which allowslarge regions to be inspected at once. This can be favourable in comparison with single crystal transducers, where multiple configurations may be required to inspect a given region.

In order to inspect a component for discontinuities, the transducer is usually coupled to the specimen via an intermediary medium to allow transfer of energy into the component. In contact mode, a solid Perspex or Rexolite wedge is commonly used for this purpose. The appropriate wedge angle will depend on the characteristics of the component and the types of flaw which are likely to occur. In immersion mode, both transducer and component are submerged in a tank filled with water, which acts as the couplant; a similar method of water couplant could be used without full immersion with water filled inspection wheels or water spray used with sledges. One advantage of using a purely liquid intermediary medium is that components with irregular surface profiles will still be fully coupled to the transducer.

To ensure an accurate representation of a component's structural integrity,an essential factor that needs to be considered is the beam path. In a situation where the beam is required to propagate through media of different acoustic velocities, the effects of refraction must be considered to determine the beam pathaccurately. The relationship between the angle of incidence and angle of refraction is given by Eq. (1), and is the well known Snell's law.

In modern day engineering Snell's law is widely applied across a broad range of industries [1–3]. In the field of ultrasonic NDT Drinkwater and Bowler [4] provide one example where the Full Matrix Capture (FMC) technique was used to inspect wrought iron chain-links for fatigue cracking. Here the array transducer was coupled to the curved surface of the chains via a solid wedge. To account for refraction at the wedge-chain interface an iterative search algorithm, using a minimum time of flight approach, was implemented. The FMC technique has also been implemented in immersion mode, where the incidentpoint along the surface profile of a component was found using a minimum time of flight algorithm [5]. A different approach by Long and Cawley [6] used a flexible membrane attached to an array transducerto inspect components with an irregular surface profile. Here curve-fitting algorithms were used to define the surface profile, and an iterative approach was used to calculate the incidentpoint at the interface.

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The purpose of the investigation presented in this work is to demonstrate how auto-focussing through dual-layered media can be achieved using analytical or numerical methods – both of which can be computationally more efficient than iterative methods. An efficient algorithm is of particular importance to FMC due to the large amount of signal processing required. In this study, ultrasonic arrays were used to acquire data using the FMC technique [7] on a low carbon steel, double 'v' butt welded plate. The ultrasonic array transducer was coupled to the test specimen via an intermediary dielectric medium. Data processing using an in-house algorithm known as Sequential Phased Array (SPA) is then discussed. This paper presents the derivation of an analytical solution for the incident point at a planar interface. It is shown how curve-fitting algorithms can enable auto-focussing through dual-layered media with a planar interface. Results are presented which illustrate how the algorithms can be applied experimentally to inspect a double 'v' butt weld in a low carbon steel plate. In addition a description of how the data processing algorithmscould be adapted to allow auto-focussing through dual media with a non-planar interface is given.

## 2. Theoretical background

### 2.1. Full Matrix Capture and the Sequential Phased Array Algorithm

FMC is a data acquisition process which collects time domain signals for every possible transmitter-receiver combination in an array transducer. This data set is termed the Full Matrix of Data. For a linear array containing $n$ elements, this yields a total of $n^2$ A-scans. Initially the first element in an array is excited, while all elements are used as receivers. This method of transmitting on one element and receiving on all is then repeated until every element within an array has been excited. An advantage of this technique, over more conventional parallel transmission methods, is that a fully focussed image can be achieved where every pixel acts as a focal point. However, while coherent noise levels of FMC are identical to that of parallel transmission techniques providedthe system is time-invariant; incoherent, random noise levels will reduce by a factor of $\sqrt{n}$ [8].

To process the Full Matrix of Data an imaging algorithm termed Sequential Phased Array (SPA) was used. This algorithm allows a fully focussed, cross-sectional image of the test specimen to be generated by treating every pixel as a focal point. For each focal point there is an amplitude contribution from every transmitter-receiver pair; each contribution is summed to give the pixel intensity. C-scan images can be produced using the SPA algorithm by stacking multiple cross-sectional images using the same methods as conventional phased array techniques [9].

### 2.2. Snell's law

The incidentpoint of a beam at aninterface between two media of acoustic velocities $v_1$ and $v_2$ can be calculated using Snell's law, expressed in its most common form in Eq. (1) and illustrated in Fig. 1, where $\theta_i$ and $\theta_R$ represent the angle of incidence and angle refraction respectively. This equation is valid for both longitudinal and shear wave modes. By setting $\theta_R$ equal to 90° for a refracted longitudinal wave mode, the first critical angle can be determined. Beyond this angle no longitudinal wave mode exists and the shear wave mode will be dominant. For a Perspex-steel interface the first critical angle will be approximately 27°.

$$\frac{\sin(\theta_i)}{v_1} = \frac{\sin(\theta_R)}{v_2} \tag{1}$$

It can be shown that Snell's law is derived from Fermat's principle [10]; by taking the derivative of the acoustic path length, the point

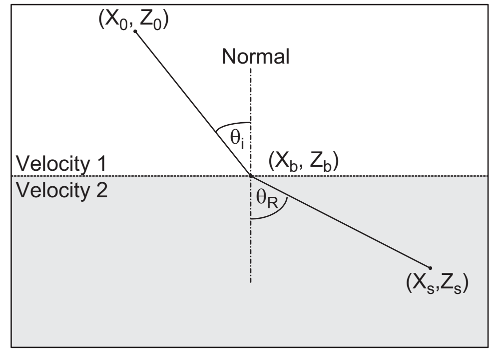


**Fig. 1.** Refraction of a wave at an interface between dual media of different acoustic velocity for a single source $(x_0,z_0)$ and target $(x_s,z_s)$.

of incidence can be determined, which allows the beam path to be calculated. The algorithms developed were based on homogeneous and isotropic bulk media which simplifies the required mathematics. We also assume that dispersion is negligible, so Snell's law holds for all frequencies across a broad spectrum.

In order to find the point of incidence at an interface, when both the target and source are well defined, it is necessary to express Snell's law in its general form (Eq. (2)). In cartesian coordinates, the position of the transducer wasdefined as $(x_0,z_0)$, the point of incidenceat the interface as $(x_b,z_b)$, and the focal point in the specimen as $(x_s,z_s)$, also shown in Fig. 1.

$$\frac{\beta(x_b-x_0)^2}{(z_b-z_0)^2+(x_b-x_0)^2} = \frac{(x_s-x_b)^2}{(z_s-z_b)^2+(x_s-x_b)^2} \tag{2}$$

where $\beta = v_2^2/v_1^2$.

In Eq. (2) all parameters except for $x_b$ and $z_b$ are known. In this paper we consider the case of a planar interface between dual layered media, whereby this interface represents zero material depth ($z_b=0$). Since $z_b$ is defined as a constant, Snell's law can be expressed as a quartic polynomial given in Eq. (3).

$$p_4x_b^4+p_3x_b^3+p_2x_b^2+p_1x_b+p_0=0 \tag{3}$$

Where the coefficients are defined as

$$p_4=\beta-1$$

$$p_3=2x_0-2\beta x_0+2x_s-2\beta x_s$$

$$p_2=-x_0^2+\beta x_0^2-4x_0x_s+4\beta x_0x_s-x_s^2+\beta x_s^2-(-z_0+z_b)^2+\beta(-z_b+z_s)^2$$

$$p_1=2x_0^2x_s-2\beta x_0^2x_s+2x_0x_s^2-2\beta x_0x_s^2+2x_s(-z_0+z_b)^2-2\beta x_0(-z_b+z_s)^2$$

$$p_0=-x_0^2x_s^2+\beta x_0^2x_s^2-x_s^2(-z_0+z_b)^2+\beta x_0^2(-z_b+z_s)^2$$

The roots of Eq. (3) can be found analytically using Ferrari's method [11], given in Appendix A. The point of incidence can then be determined by finding the path of minimum time.

Snell's law can also be used to find the point of incidence at a non-planar interface, provided such an interface is well defined. The equation which governs this scenario is not expressed here, but is presented in Appendix B. Since this equation is non-polynomial and the exponent of the variable exceeds 4th order, solutions must be found using numerical or iterative methods. For a planar interface the point of incidence will always be that which yields the minimum time of flight. However, in the case of a non-planar interface, it is possible for the point of incidence to be located at one or more local minima or maxima. Fig. 2a shows the time of flight of a wave propagating from a transmitter to a receiver through a quadratic interface as a function of the point of incidence. The simulated beam path in Fig. 2b shows the wave to be incident at the point along the interface which corresponds to a local maximum time of flight. This satisfies Fermat's principle