NUMERICAL MODELING AND IMAGING OF THREE-DIMENSIONAL TRANSDUCER FIELDS IN ANISOTROPIC MATERIALS

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INTRODUCTION

Piezoelectric transducers are the basic tool for ultrasonic NDE applications and are commercially available in a variety of sizes, shapes and frequencies. However, the information that is typically provided for these transducers by vendors is of limited value. This is especially true when it comes to testing anisotropic materials. The wave propagation effects such as beam skewing, splitting and distortion, when taken into experimental consideration for anisotropic media, requires knowledge of the spatial radiation field distribution of the transmitting transducer. In this paper, a previously developed methodology to map the radiation fields for piezoelectric transducers [1] is applied to imaging (mapping) three dimensional radiation fields generated by transducers of various shapes and frequencies placed in contact with anisotropic propagation media. The processed data files are calculated for transversely isotropic materials via the Generalized-Point-Source-Synthesis (GPSS) method [2,3]. The material is regarded to be homogeneous since the ultrasonic wavelength is larger than the grain dimensions. A computationally efficient version of GPSS is used for modeling the quasi-longitudinal (quasi-pressure) wave [4]. Emphasis is placed on these waves, since they are of particular interest in nondestructive ultrasonic testing of austenitic weldments. The synthetic data is transferred to an imaging workstation, where the 3-D transducer fields are displayed using commercially available graphic packages. The fields of circular transducers of various frequencies are shown for different austenitic weld material configurations. For reference purposes, fields in an isotropic base material are also shown using the same transducers. In closing, the implications of such 3-D mappings are discussed.

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COMPUTATIONAL MODEL

Based on a theory of elastic wave propagation in transversely isotropic media, the GPSS method has been developed to model the radiation, propagation and scattering of elastic waves as generated by ultrasonic transducers in these media [2,3]. The physical basis of the method is Huygens' principle which states that *each point of a wave front is the starting point of an elementary wave, the new wave front is obtained from the superposition of all such elementary waves*. Accordingly, the displacement vector [2] describing the transducer generated α - *wave* field is given by

$$\underline{u}^{\alpha}(\underline{R}) = \sum_{m} \left\{ \hat{\underline{u}}^{\alpha}(\theta_m, \underline{a}_{rot}) \bullet \frac{exp\left(\left(-j\omega \left|\underline{R} - \underline{R}_m\right|\right) / \left|\underline{c}_{\alpha}(\theta_m, \underline{a}_{rot})\right| \right)}{\left|\underline{R} - \underline{R}_m\right|} \bullet \Gamma^{i\alpha}_{point}(\theta_m, \underline{a}_{rot}) \right\} \tag{1}$$

where $\underline{R}_m$ designates the position of the m^{th} tangential ($i = x, y$) or normal ($i = z$) point source on the transducer surface in contact with the material, α denotes the propagation mode of the wave (e.g., for isotropic case: $\alpha = SH, SV$ or P; for transversely isotropic case it is SH, qSV or qP). The directional dependence of group velocities $\underline{c}_{\alpha}$, the polarizations $\hat{\underline{u}}^{\alpha}$ and the directivity $\Gamma^{i\alpha}_{point}$ is expressed in terms of θ_m, which is the angle of insonification producing a contribution of the m^{th} point source in the direction $(\underline{R} - \underline{R}_m)$ (see Fig. 1) and $\underline{a}_{rot}$ is material orientation vector. In Fig. 1, Ψ_m is the angle of energy flow and Δ is the skewing angle due to possible difference between phase and energy flow direction in anisotropic material. As we shall see, the skewing angle is zero for propagation inside an isotropic material. Equation (1) is a most general expression for displacement at any point $\underline{R}$ valid for any anisotropic medium. A detailed description of Eq. (1) and the determination of directivity function $\Gamma^{i\alpha}_{point}$ for arbitrarily oriented transversely isotropic media is given in Ref. [2].

An improved version of GPSS has been developed for accelerated space-time modeling of quasi-longitudinal waves in austenitic weld structures [4] and is applied to calculate the synthetic data used for creating 3-D images of radiation fields inside columnar-grained steel.

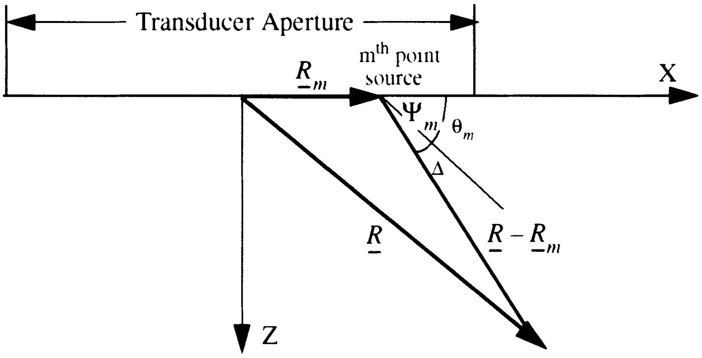


Figure 1. Geometrical scheme for calculation of displacement field.

THREE- DIMENSIONAL IMAGING

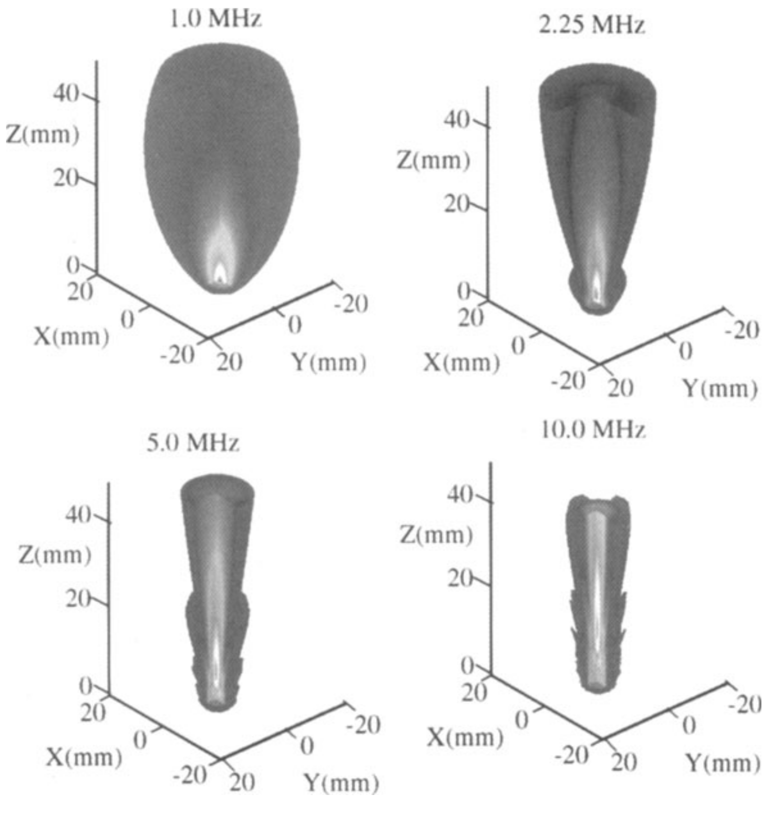
We assume that the columnar-grained weld material can be described as homogeneous and transversely isotropic with the *c*-axis parallel to the columnar grains. The sound radiation field is generated by a circular longitudinal wave transducer insonifying the transversely isotropic media at 15^0 and 45^0 to the *c*-axis, respectively. The field due to contact circular transducers of frequencies 1.0 MHz, 2.25 MHz, 5.0 MHz and 10.0 MHz and each of diameter 6.3 mm were modeled successively for propagation in specimens of size 50 x 40 x 40 mm^3 (Y-X-Z). It is assumed that the transducer is at the surface Z = 0 with center at X = Y = 0. To map the three dimensional transducer field inside the medium, for each fixed value of Y (-20.0 mm to 20.0 mm in steps of 0.4 mm), Z (0 to 50.0 mm) and X (-20.0 mm to 20.0 mm) are varied in steps of 0.4 mm sequentially. At time t = 0, the transducer sends out a quasi-monochromatic longitudinal pulse at normal incidence. For each coordinate point under this scanning scheme, the value of the displacement field inside the medium is computed for quasi-pressure ($\alpha = qP$) wave from Eq. (1). A fast algorithm using GPSS creates a data file for each frequency. Three-dimensional visualization of modeled data was performed using a commercial visualization package. This package then generates a 3-D image of the radiation field as seen inside the anisotropic medium for a given frequency. For each frequency, the angle of grains relative to the material surface is varied, i.e., the angle of *c* axis for the transversely isotropic material.

RESULTS AND DISCUSSION

Figure 2 shows longitudinal field in an isotropic material at 1.0, 2.25, 5.0 and 10.0 MHz. The radiation field is symmetrical around Z-axis. Also as one increases the frequency, the number of side lobes increase. For the anisotropic case of 45° columnar grains (Fig. 3), there is some distortion of the field but there is practically no skewing of the longitudinal transducer field in the medium. However, for the case of the quasi-longitudinal field in 15°columnar grains, the field is skewed (Fig. 4)

The beam skewing effects become more obvious in Figs. 5, 6 and 7 which depict a plane cross-section of the fields in these materials at X = 0 (YZ plane).This is in concurrence with the effect of anisotropy on the propagating field as shown in Fig. 8. For propagation in isotropic medium, the field is symmetrical along propagation direction. This is not the case for propagation of quasi-pressure waves launched into the anisotropic steel as shown in Figs. 6 and 7 for columnar grains oriented 15 ° and 45 ° to the surface.

The skewing behavior is a function of the orientation of anisotropic columnar grains. Illustrated in Fig. 8 is an example of skewing angle Δ as a function of insonification angle θ. As discussed previously there is almost no skewing at an insonification angle of 45°. Very little skewing would be anticipated at 45° because the steel has cubic crystallographic structure and the transversely isotropic assumption is that the unit cell dimensions $a = b \approx c$ for this particular case. Good agreement with experimental C-Scan results have been obtained for austenitic weld material and shown previously in Ref. 3, thus indicating the correctness and validity of GPSS.



1.0 MHz

2.25 MHz

5.0 MHz

10.0 MHz

Figure 2. Longitudinal pressure field in an isotropic base material at various frequencies.

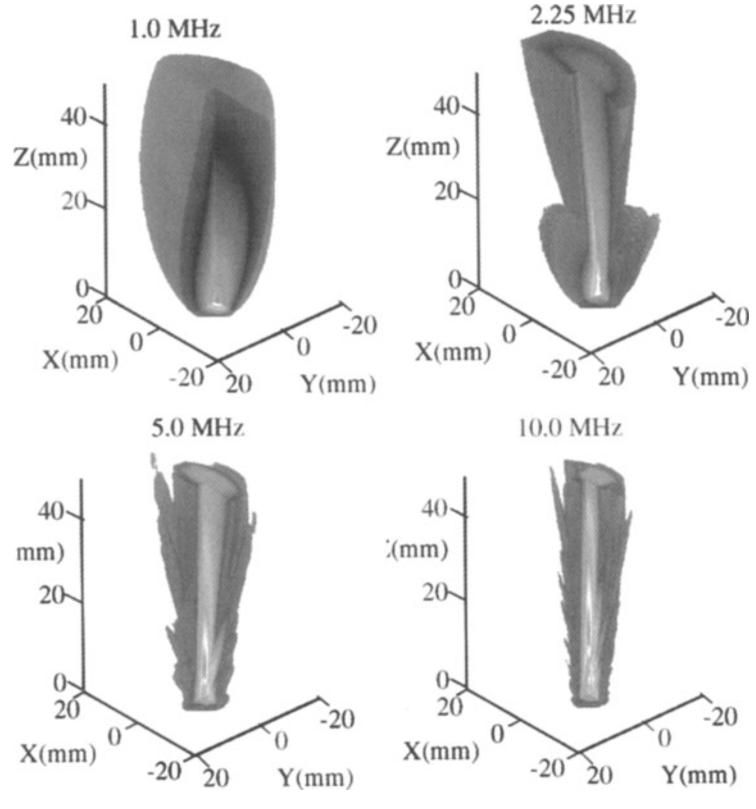


Figure 3. Longitudinal pressure field due to contact transducers in 45^{0} columnar steel.

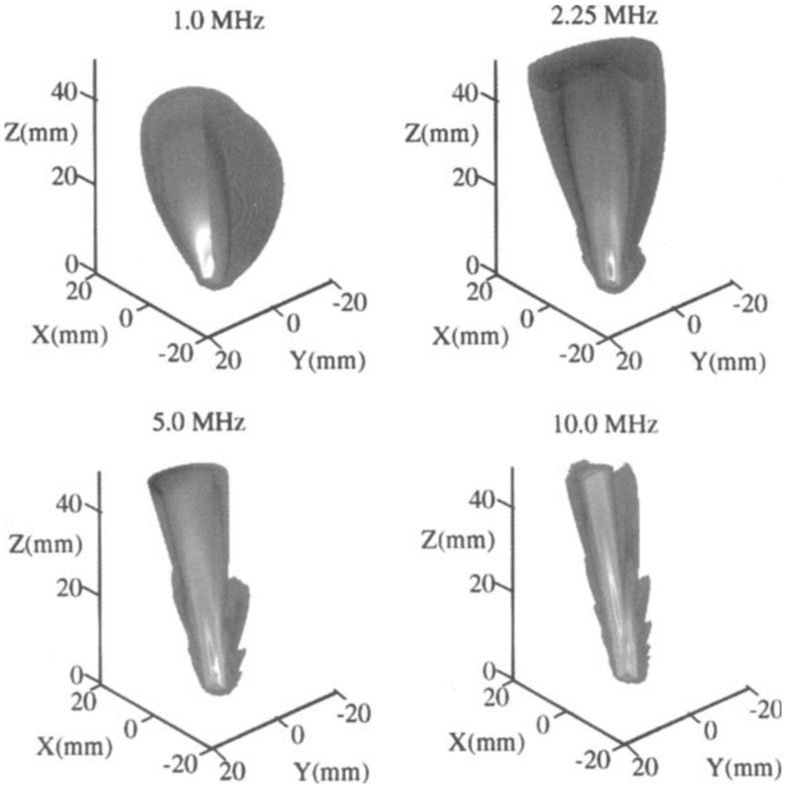


Figure 4. Skewed longitudinal pressure field inside 15^{0} columnar steel.

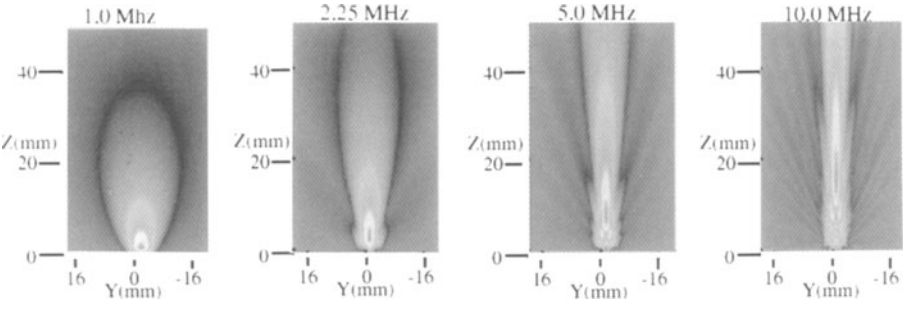


Figure 5. Cross-section of computed pressure field in an isotropic base material along the propagation direction at various frequencies.

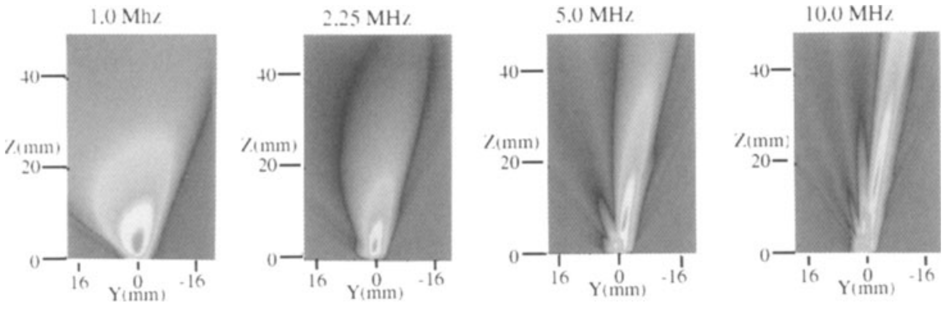


Figure 6. Pressure field along Z-axis in 15° columnar steel at X = 0 plane for 1.0, 2.25, 5.0 and 10.0 MHz.

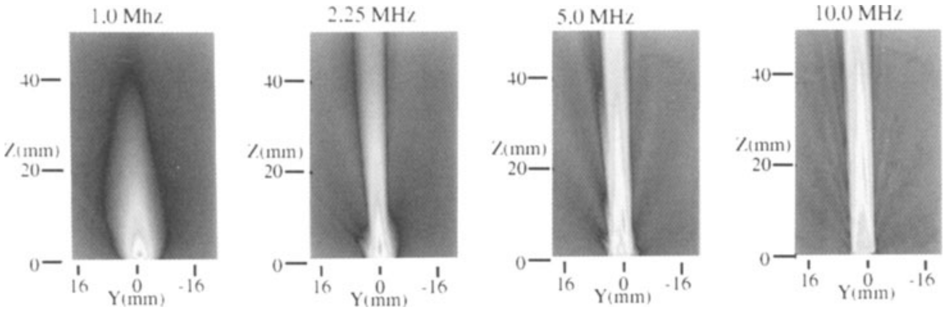


Figure 7. Pressure field along Z-axis in steel with columns at 45° for 1.0, 2.25, 5.0 and 10.0 MHz. Notice there is less skewness than at 15°.

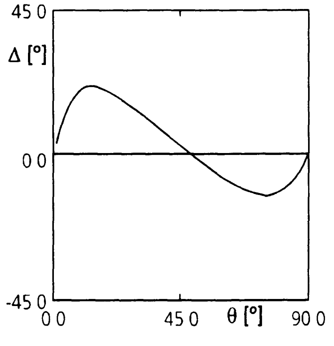


Figure 8. Skewing in anisotropic materials as a function of orientation of grains.

SUMMARY

In this paper we have shown computer generated 3-D quasi-pressure amplitude mappings of circular aperture transducers at different frequencies for propagation in an idealized transversely isotropic austenitic steel and in isotropic base materials. We have shown that from such 3-D patterns, one can obtain the amplitude at any spatial point inside the medium. These three dimensional mappings could be useful in transducer design for NDT characterization of anisotropic materials; in this study we have chosen austenitic weld materials for illustration. The 3D-mappings provide comprehensive information, which is most useful also in view of optimizing ultrasonic testing methods.

REFERENCES

1. N.K. Batra, K.E. Simmonds, H.H. Chaskelis and R.B. Mignogna, "Mappings of Three-Dimensional Radiation Field of Ultrasonic Transducers", in *Review of Progress in QNDE*, Vol. 14, eds. D.O. Thompson and D. E. Chimenti, Plenum Press, New York (1995), 1029-1036.
2. M. Spies, "Transducer-Modelling in General Transversely Isotropic Media Via Point-Source-Synthesis. Theory," J. Nondestr. Eval. 13, 85-99 (1994).
3. M.Spies, F. Walte, "Application-Directed Modelling of Radiation and Propagation of Elastic Waves in Anisotropic Waves in Anisotropic Media: GPSS an OpoSSM," in *Review of Progress in QNDE*, Vol. 14, eds. D.O. Thompson and D. E. Chimenti, Plenum Press, New York (1995), 1013-1020.
4. M. Spies, M. Kroning, "Accelerated Space-Time Modelling of Quasi-Longitudinal Waves in Austenitic Weld Structures," these proceedings.