APPLICATION OF MEASUREMENT MODELS TO SPECIFICATION OF ULTRASONIC INSPECTIONS

T. A. Gray
Center for Nondestructive Evaluation
Iowa State University
Ames, IA 50011

INTRODUCTION

For economic reasons, there is an increasing tendency to perform automated ultrasonic scans of near net-shaped forgings, which can have rather complex shapes, as opposed to inspection of simpler, sonic shapes, which typically have only planar inspection surfaces. A difficulty in the former approach is that the surface curvature of forgings causes the ultrasonic beam to focus or defocus within the component and, therefore, the ultrasonic sensitivity to internal defects changes as compared to inspection through a flat surface. It is certainly possible to account for this sensitivity variation by using curved calibration or reference blocks. However, a more convenient and cost effective approach is to use analytical models to predict the UT instrument gain corrections required for the curved surface inspections as compared to sensitivity levels measured from standard flat surface calibration blocks. This paper describes such models and their application to specification of ultrasonic inspection parameters for scanned ultrasonic inspection of curved forgings using both planar and focused transducers. Examples of these applications will be presented via case histories from the electric generation and aircraft engine industries.

ULTRASONIC MEASUREMENT MODEL

The UT measurement model is based upon Auld's electromechanical reciprocity relationship [1]. Flaws are assumed to occur within the bulk of an isotropic, homogeneous, elastic medium. It is further assumed that the flaw dimensions are small with respect to the ultrasonic beam size and that their scattering amplitudes do not vary significantly over the range of angles subtended by the transducer. The ultrasonic inspection method is assumed to be pulse-echo. This results in a relatively simple ultrasonic measurement model in which the ultrasonic beam propagation effects and the scattering effects are separable [2]. The model predicts the time harmonic (single frequency) response caused by the presence of a scatterer in the ultrasonic beam.

Ultrasonic beam propagation and transmission and/or refraction through curved liquid-solid interfaces are represented by the Gaussian-Hermite beam model, in which a time harmonic ultrasonic displacement or velocity field is represented as a summation of

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 16
Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1997

Gaussian-Hermite functions [3]. This model employs paraxial approximations, whose accuracy is best near the beam axis and for cases where incident angles in the beam footprint on the component surface are not near critical angles. This model is used to predict bulk propagating waves only. Scattering amplitudes for circular flat-bottomed holes are modeled using the elastodynamic Kirchhoff approximation [4]. This model accurately predicts the specular reflection from a planar reflector, but does not correctly represent edge diffraction or surface waves on the face of the reflector.

To predict broad bandwidth waveforms, the time harmonic results just described must be convolved with the system response of an ultrasonic instrument. This is accomplished by extracting a system efficiency factor [2] from a reference waveform, such as the echo from a planar surface, and multiplying its frequency components times the time harmonic components representing the beam and scattering amplitudes. The resulting spectrum is inverse Fourier transformed to generate a time domain RF waveform.

In order to model UT inspectability characteristics of forgings, which may have entry surfaces of complex shape, it is necessary to know the appropriate geometrical parameters that define the component's surface. In the work described herein, the geometrical descriptions (coordinates of surface points, normal vectors, principal radii of curvature) of the forgings have been extracted from CAD models. Further description of this approach and other applications of a graphical ultrasonic simulator, denoted *UTSIM*, can be found in reference [5].

APPLICATIONS

Specification of UT inspection properties for forgings is generally performed by empirical "cut and try" approaches, requiring a variety of calibration standards and/or reference specimens that are geometrically similar to portions of the forging. Specification of new hardware, e.g. nonstandard UT transducers, can present even more of a challenge without recourse to analytical UT modeling tools. Here we apply UT measurement models to these problems via three examples – (i) predicting instrument gain modifications needed for planar probe inspection through curved surfaces, (ii) design of transducer properties for focused inspection of forgings, and (iii) visualization of scanned UT capability for forging inspection.

Curvature Correction Factors for Forging Inspection

In this example, models are applied to the problem of specifying UT instrument gain settings needed to compensate for inspection through curved forging surfaces using planar transducers. This would be a typical application for inspection of large steam turbine disk forgings such as are used in electric power generation equipment. It is assumed that a distance amplitude curve (DAC) is measured on standard, flat-surfaced calibration blocks containing flat-bottomed hole (FBH) reflectors. The modeling goal is to predict the changes in instrument gain required to yield the same DAC when the FBH reflectors are situated below a curved surface. Representative model results for normal incidence longitudinal waves using a planar immersion transducer with a 0.5 inch diameter crystal, 2.25 MHz center frequency, and 40% bandwidth are shown in Figure 1. The heavy solid line in the figure represents the flat surface DAC and the remaining curves are the curvature correction factors (CCFs) for concave, cylindrical surfaces with 1 inch, 3 inch and 6 inch radii of curvature, respectively. That is, these curves are the additional depth dependent gain which must be added (or subtracted) to achieve the flat surface DAC curve. Note that the CCFs are predominantly negative because the concave forging entry surface

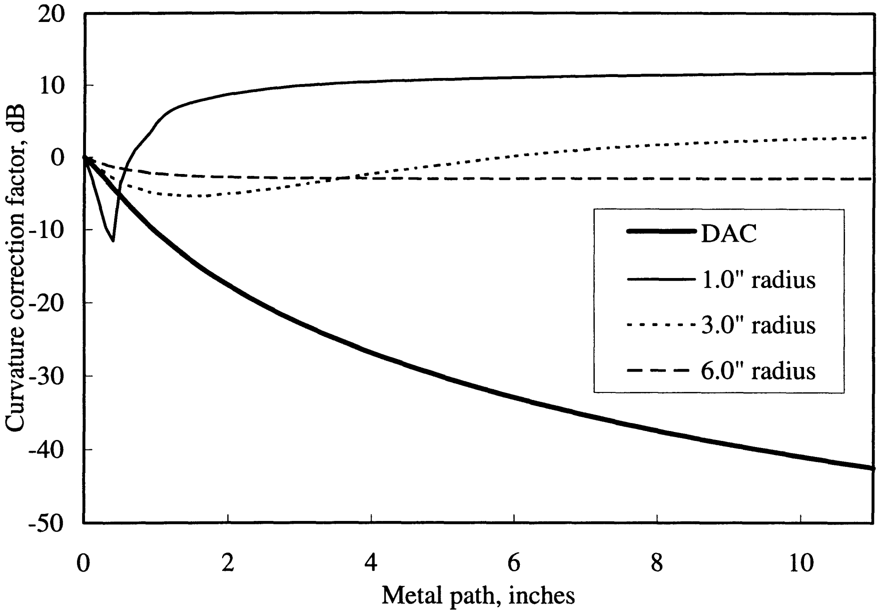

Figure 1. Model predicted curvature correction factors for 1 inch radius grooves with out-of-plane curvature as shown in the legend using normal incidence L-wave inspection using a 2.25 MHz, 0.5 inch diameter transducer.

acts like a focusing lens. However, for the 1 inch radius groove, the sharp focus occuring at a ~0.5 inch depth is followed by a diverging beam beyond the focal zone, which is evident in the positive CCF in that region. Figure 2 shows that the CCF computed for a straight cylindrical groove differs only slightly (within 2 dB) from those for either a concave-concave or concave-convex biradial groove with a 14 inch swept radius.

Probe design and Curvature Correction for Focused UT Inspection of Forgings

The second example considers the problem of specifying a focused probe UT inspection in an axially symmetric forging. For this example, the nominal transducer is a 5 MHz, 60% bandwidth probe with a 0.75 inch diameter crystal and a point target focal length in water of 6 inches. (The model uses a "geometric" focal length [6], which represents the radius of phase curvature immediately in front of the lens; the geometric focal length for this probe is 8.2 inches.) The goal is to achieve the same focal zone below a curved forging surface with a 3 inch concave radius of curvature as can be achieved in the focal zone of the spherically focused transducer with a 3 inch water path to a planar surface. The first objective, then, is to determine the appropriate transducer characteristics that will yield the desired focal characteristics. Transducer parameters (elliptical crystal semiaxes and biradial lens focal lengths) and water path length were varied systematically to best fit the focal distance and -3dB depth of field below the curved surface to those focal properties in the planar surface situation. Figure 3 shows a comparison of the on-axis amplitudes for the two cases. The optimized transducer has a 0.24 x 0.75 inch crystal, a bicylindrical lens with geometrical focal lengths of -60 x 8.3 inches, and a water path of 2.8 inches. Note that the lens has a negative focal length (defocusing, or, convex lens) in one dimension to compensate for the focusing effect of the concave forging surface. To assess

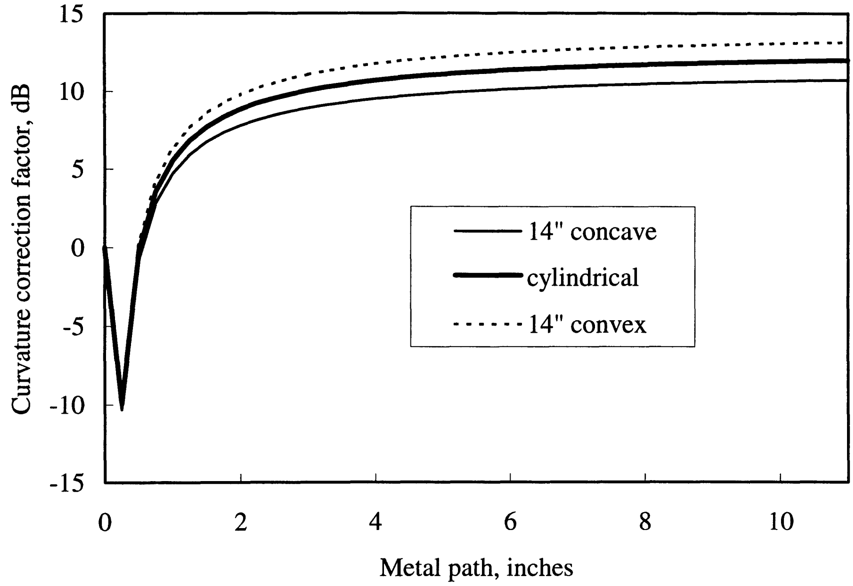

Figure 2. Model predicted curvature correction factors for 1 inch radius grooves with out-of-plane curvature as shown in the legend using normal incidence L-wave inspection using a 2.25 MHz, 0.5 inch diameter transducer.

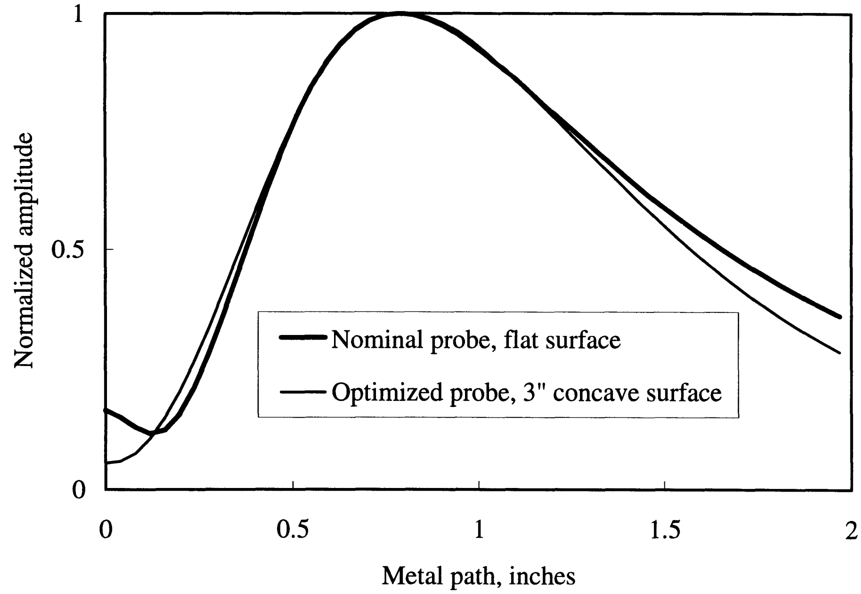

Figure 3. Comparison of focal zones for nominal spherically focused probe on a flat surface and optimized elliptical, aspherical focused probe on a 3" radius of curvature concave surface.

the range of applicability of such a transducer, axial fields were computed for this probe when applied to a 2.5 inch and a 3.5 inch radius surface. Curvature correction factors relative to the 3 inch radius surface are shown in Figure 4. This figure shows that only modest gain corrections are needed to use the optimized probe for surface geometries that are different than those for which it was defined. As a final comment in this example, it should be pointed out that focusing properties similar to those of the optimized probe can be achieved by other means, such with the aid of curved acoustic mirrors or by using array technology. Straightforward extensions of the techniques described in this paper could be used to specify inspection parameters in those cases.

Visualization of Scan Capability

In the final example, an axially symmetric, near net shape forging is to be ultrasonically inspected using a 0.375 inch diameter, 3 inch focal length, 10 MHz, 60% bandwidth transducer with the probe at normal incidence and focused on the forging surface. It is assumed that the forging is rotated on a turntable and that the probe is indexed within a radial-axial plane. The goal in this application is to determine sensitivity levels to small #1 FBH-equivalent scatterers within the forging in order to locate potential "blind spots" in the final machined shape. For example, Figure 5 shows a greyscale display of signal amplitude, in volts, versus position within the forging cross-section assuming that the forging is scanned with the probe on the "inside" of the component (i.e. the probe is to the lower left of the image). The final forging shape is superimposed on the image and can be seen as a white contour. The bright, higher amplitude regions adjacent to concave entry surfaces arise due to geometrical focusing. The abrupt transitions in greyscale intensity in various parts of the image are caused by the model's computation of surface transmission effects using the surface curvatures encountered by the central axis of the beam. Figure 6 shows similar results, except this time the probe is assumed to be on the "outside" of the forging. Figure 7 is a composite of the preceding two figures, with the greyscale value at each interior point defined by the maximum value from the interior and exterior scan values. Based upon the results in that figure, it would appear that the signal amplitudes in lower left portion of the forging are low. However, if the signal amplitudes are corrected using a time variable gain (gain versus metal path measured below a flat surface), then Figure 8 is the result. Here, we see that the apparent low amplitude region seen in the lower left portion of Figure 7 is actually no worse than would be measured through a planar surface. The computations at each point in these assume that scatterers in the forging have the same reflectivity as a #1 FBH at that point oriented perpendicular to the ultrasonic beam. In actual forgings, flaw shapes and orientations tend to align with the forging flow directions, so a full analysis of inspectability needs to include that type of variability. These effects can be treated by the current models, but no basis for assigning forging flow patterns was available during the analysis.

SUMMARY

This paper demonstrated several examples of the application of analytical models to problems associated with specification of ultrasonic inspection of forgings. These included computing curvature correction factors for inspection through curved surfaces, determining transducer parameters to achieve desired focal properties below a curved surface, and visualizing UT inspection capability for complex shaped forgings. The examples showed the utility of model-based approaches. It should be noted that a variety of simplifying assumptions were made. For example, effects of grain scattering (noise and attenuation), surface roughness, material anisotropy due to forging flow, etc. were not considered in the

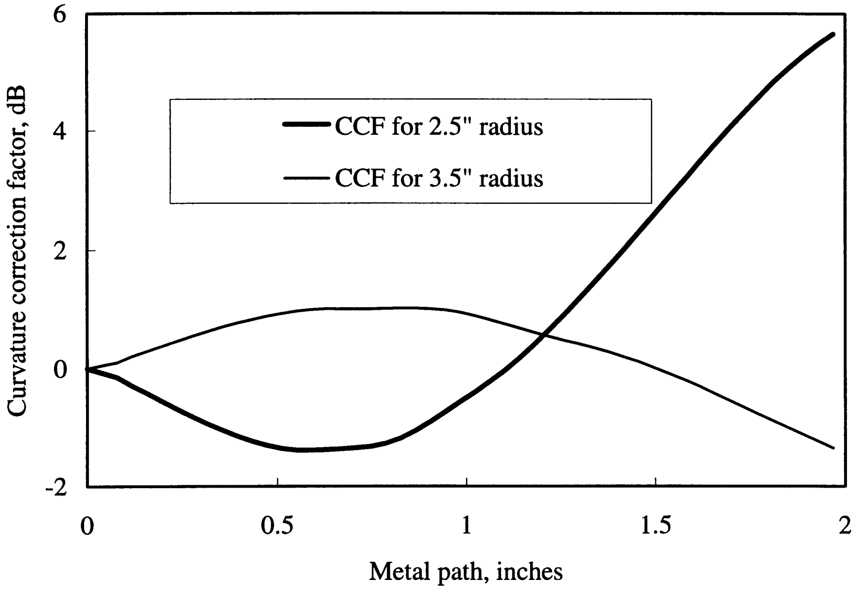

Figure 4. Curvature correction factors for optimized probe in Figure 3 when used on 2.5" or 3.5" radius of curvature concave surfaces.

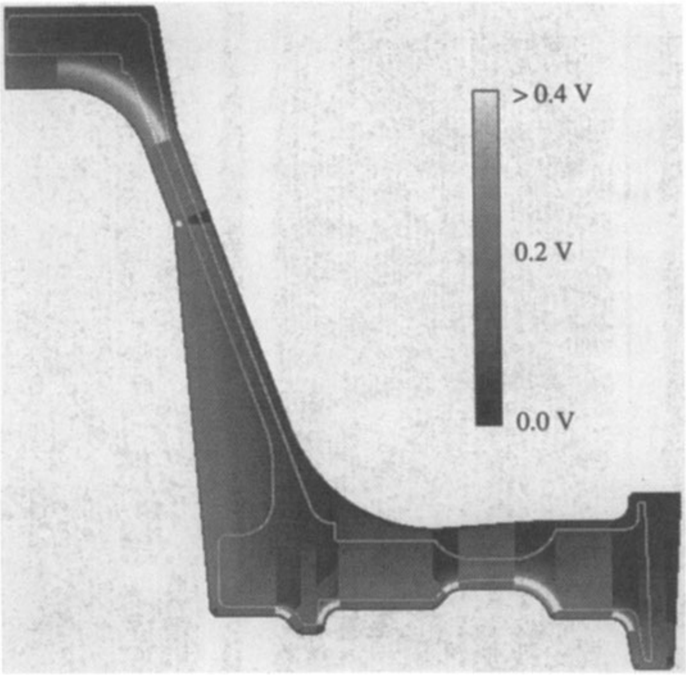

Figure 5. Signal amplitude map for #1 FBH equivalent reflectors in forging geometry. Scan points chosen only on "inside" of forging, i.e., relatively lower left boundary of forging. White outline inside image is the final machined shape.

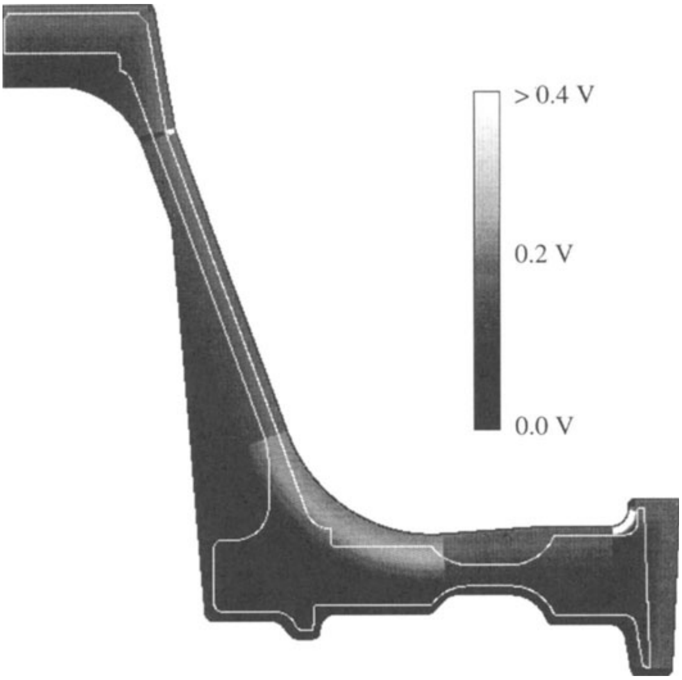

Figure 6. Signal amplitude map for #1 FBH equivalent reflectors in forging geometry. Scan points chosen only on "outside" of forging, i.e., relatively upper right boundary of forging.

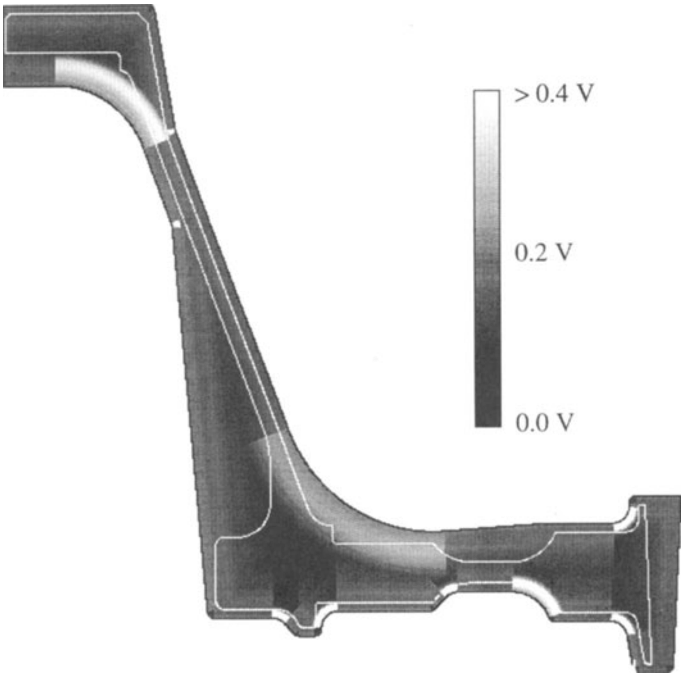

Figure 7. Signal amplitude map for #1 FBH equivalent reflectors in forging geometry for scan around entire forging shape.

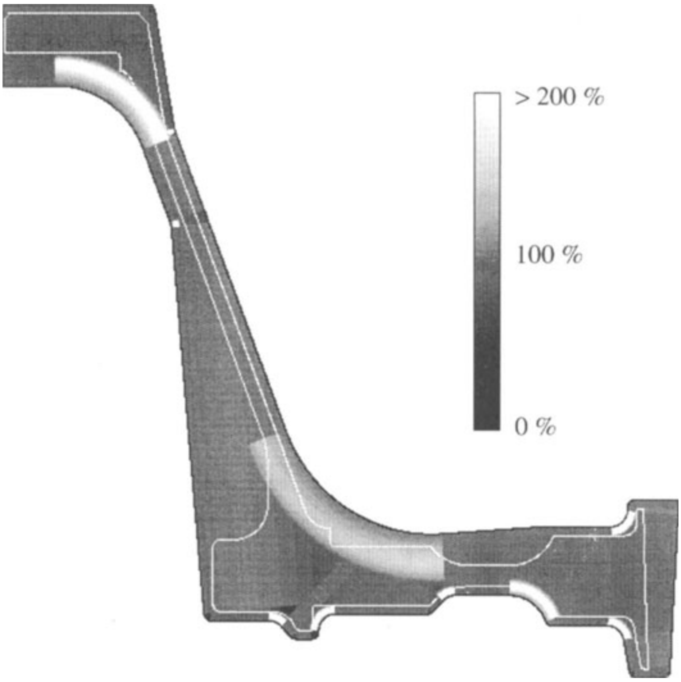

Figure 8. Signal amplitude map for #1 FBH equivalent reflectors in forging geometry for scan around entire forging shape. Amplitudes are expressed relative to DAC curve from flat surface calibration blocks.

analyses. These effects are, however, the subject of ongoing research and will be incorporated into the simulations in the near future.

ACKNOWLEDGMENT

Portions of this work were performed under the sponsorship of the U. S. Department of Commerce, National Institute of Standards and Technology; other portions were performed under the sponsorship of the Engine Titanium Consortium, supported by the Federal Aviation Administration under Grant number 94G048. The author also wishes to acknowledge P. Zombo of Westinghouse Electric Corporation, U. Suh and D. Sturges of General Electric Quality Technology Center, and K. Smith of Pratt & Whitney for their contributions to this work.

REFERENCES

1. B. A. Auld, *Wave Motion 1*, 3 (1979).
2. R. B. Thompson and T. A. Gray, *J. Acoust. Soc. Am. 74*, 1279 (1983).
3. R. B. Thompson, T. A. Gray, J. H. Rose, V. G. Kogan, and E. F. Lopes, *J. Acoust. Soc. Am. 92*, 1818 (1987).
4. L. Adler and J. D. Achenbach, *J. Nond. Eval. 1*, 87 (1980).
5. M. Garton, T. A. Gray and A. Minachi, in *Review of Progress in QNDE*, Vol. 16, eds. D. O. Thompson and D. E. Chimenti, (Plenum Press, New York, in the press).
6. F. Amin, T. A. Gray and F. J. Margetan, in *Review of Progress in QNDE*, Vol. 10, eds. D. O. Thompson and D. E. Chimenti, (Plenum Press, New York, 1991), p. 861.