EXPERIENCES IN THE USE OF GUIDED ULTRASONIC WAVES TO SCAN STRUCTURES

R. Bruce Thompson
Center for Nondestructive Evaluation
Iowa State University
Ames, Iowa 50011

INTRODUCTION

The use of guided ultrasonic waves to rapidly interrogate large structures is a topic that is currently receiving considerable attention. The purpose of this paper, and the companion paper by Alers [1], is to briefly review some past experience that may not be readily available to current researchers since many of the results were not presented in archival publications. The work described in this paper was conducted in the context of exploring applications of electromagnetic-acoustic transducers (EMATs) [2,3] as a part of the NDE effort at the Rockwell International Science Center in the period 1970-1980. In addition to the author, others playing key roles in various parts of this effort included G. A. Alers, R. K. Elsley, C. M. Fortunko, M.W. Mahoney and C. F. Vasile. The companion paper by Alers includes subsequent developments at the private company, Magnasonics, Inc. as well as more recent work at the National Institute of Standards and Technology. Although EMAT's were used in all of this work as the sensors to excite and detect the guided ultrasonic modes, the basic ideas apply to the use of guided modes excited by any kind of sensor to scan structures.

A few of the photographs in this paper may reproduce with a rather low quality. The author apologizes to the reader for this situation, which is a consequence of original photographs no longer being available.

FUNDAMENTAL CONCEPTS

There are two primary motivations for using guided modes to detect flaws. First, one wishes to increase the speed of inspection. As an ultrasonic wave propagates at speeds on the order of kilometers per second, it passes through a material much more quickly than a transducer can be scanned over the surface. Second, one wishes to gain information from remote locations where a transducer can not be placed.

There are several trade-off issues which must be addressed in developing a successful application. In order to easily interpret the information gained in the inspection, it is desirable that a transducer excite a single mode. Consider the dispersion curve shown in Fig. 1a. Single mode operation can be achieved when the range of frequencies and wavevectors excited by the probe are sufficiently small that there is insignificant excitation energy for all but the intended mode. For the case of EMATs, this can be accomplished through the use of sufficiently long probes excited by tone bursts of sufficient duration [3]. There is, however, a loss of the ability to resolve flaws from other nearby discontinuities with these increases in the spatial and temporal lengths of the excitation.

Given unambiguous information obtained by single mode operation, one needs to ensure that there is sufficiently large signal-to-noise ratios (SNR) to allow small flaws to be detected. Factors that influence the SNR include the efficiency of the transduction, propagation losses and the strength of the scattering of the particular mode selected by the flaw. When using guided modes, the efficiency of the transduction can depend dramatically on the relative directions of the tractions exerted by the probe on the part surface and the displacements of the guided mode motion at the surface of the part. These effects are graphically illustrated in Figs. 1b and 1c. The mode admittances, shown as the ordinate, are defined as the ratio of the power carried by the mode to the square of the displacement of a particular component of the mode's surface motion. When

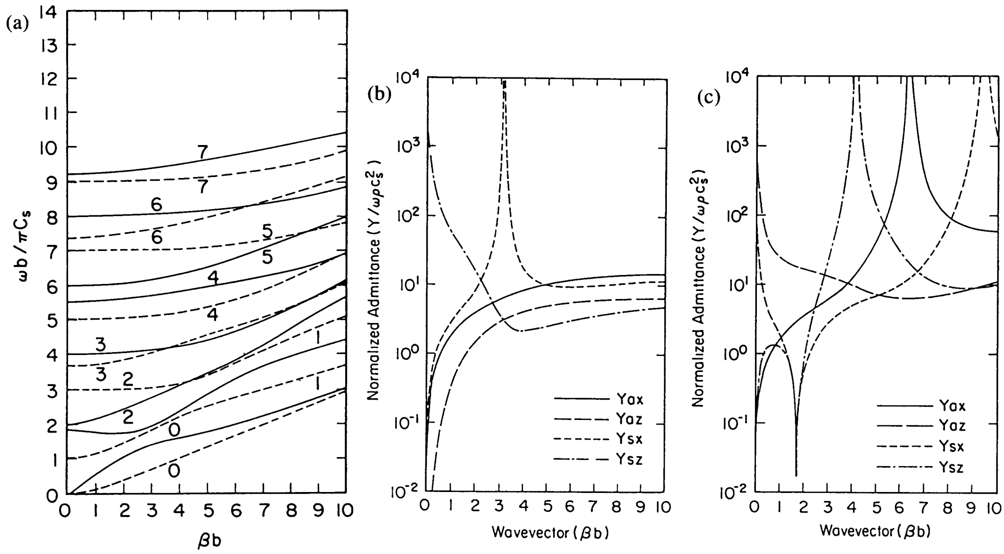


Figure 1. Design of EMATs: (a) dispersion curves used for mode selectivity; (b) & (c) admittance curves used to maximize efficiency.

this number is low, implying a large surface displacement, the mode can be efficiently excited by a traction in the same direction as the displacement. These ideas are discussed quantitatively in Ref. [3] for the case of EMATs, but are equally relevant to modes excited by other types of transducers which operate by imposing a surface traction in a particular direction.

When flaw characterization is desired, one might want to use multiple modes, and the selectivity of the scattering, i.e. the degree to which different modes interact with the flaw in different ways becomes an important factor.

EARLY SYSTEMS

Using these elementary ideas, systems using guided modes to inspect a variety of structural components were developed. Three examples which received considerable effort are discussed below.

Buried Pipelines

Under the support of the Pipeline Research Committee of the American Gas Association, a "pig" was developed to inspect buried natural gas pipelines using guided modes, propagating around the circumference [2, 4-6]. Figure 2 shows an early laboratory prototype [5] and a well developed robot used in field tests [2]. An important element of the design was the optimization of the magnetic field strength to fully utilize magnetostrictive contributions to the EMAT efficiency [3].

To test these ideas, a series of "defects" were machined into the outer surface of a 40 foot length of 36 inch diameter, buried pipe, with the dimensions provided in Table I. As examples of the data obtained, Figure 3 presents a typical set of waveforms, obtained with the Ao (flexural) mode at 130 kHz. Shown are the arrivals of waves propagating clockwise from transmitter to receiver along a short path (1), reflecting back to the receiver from a flaw (2), propagating counterclockwise from the transmitter to receiver along a long path (3), and reflecting from a weld (4). Fig. 4 compares the strengths of the reflected signals for waves reflected from the slots (a) and flat-bottom holes (b). As would be expected, the former give appreciably larger signals. In this implementation, dish-shaped defects simulating corrosion were very difficult to detect by reflection. However, it was found that such defects could be readily detected via the changes they produced in the transmission of a guided mode. Figure 5 presents both the shift in arrival time and amplitude for such a situation, results which can be interpreted in terms of dispersion and focusing effects. In essence, due to the thickness dependence of the velocity, the dishes act as lens. Given the differing responses of these classes of defects in reflection and transmission, an elementary defect classification scheme was developed as shown in Fig. 6, in which the reflection coefficient is plotted versus the transmitted arrival time shift.

Artillery Projectiles

Under the support of the U. S. Army, similar ideas were applied to the inspection of artillery projectiles, using the configuration illustrated in Fig. 7 [5,7,8]. Here 2.25 MHz Rayleigh waves were used to scan the exterior surface for defects while 1.8 MHz angle shear waves were used to examine the interior of the wall and the inner surface. The amplitude of the Rayleigh waves was enhanced by magnetostrictive effects. Defects as small as 0.1" by 0.01" were detected in the Rayleigh wave mode.

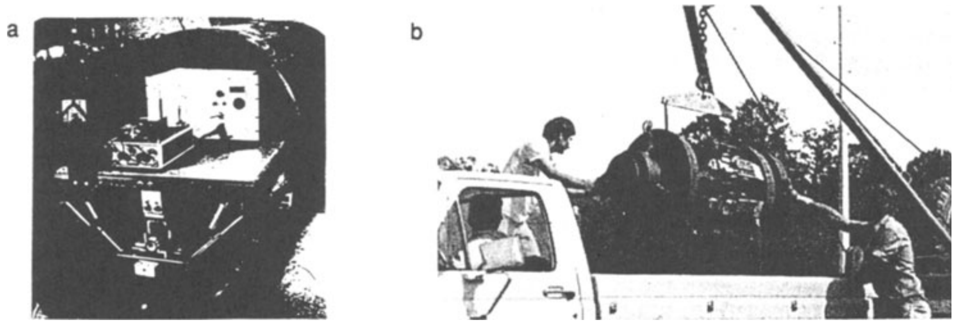


Figure 2. EMAT systems for inspecting buried natural gas pipelines: (a). early laboratory prototype (after Ref.[5]); (b). well developed instrument for field use (After Ref. [2]).

Table I Dimensions of "defects" machined into outer surface of buried pipe. D is diameter and L is maximum depth.

	No	Distance from South End (ft)	D (in)	L (in)		No	Distance from South End (ft)	D (in)	L (in)
Ground	1	5-1/2	10	090	Tapered	11	22	1	1/4
Circular	2	7	7	110	Bottom	12	22-1/2	1	1/8
Dish	3	8-1/2	4	180	Holes	13	23	3/4	3/16
Depressions	4	9-1/2	2	330		14	23-1/2	3/4	3/32
						15	24	1/2	1/8
						16	24-1/2	1/2	1/16
Flat	5	14-1/2	1	1/4	Longitudinal	17	30	10	090
Bottom	6	15	3/4	1/4	Slots	18	31-1/2	7	110
Holes	7	15-1/2	1	1/8		19	33	4	180
	8	16	3/4	1/8		20	34	2	330
	9	16-1/2	1/2	1/8					
	10	17	1/2	1/8					

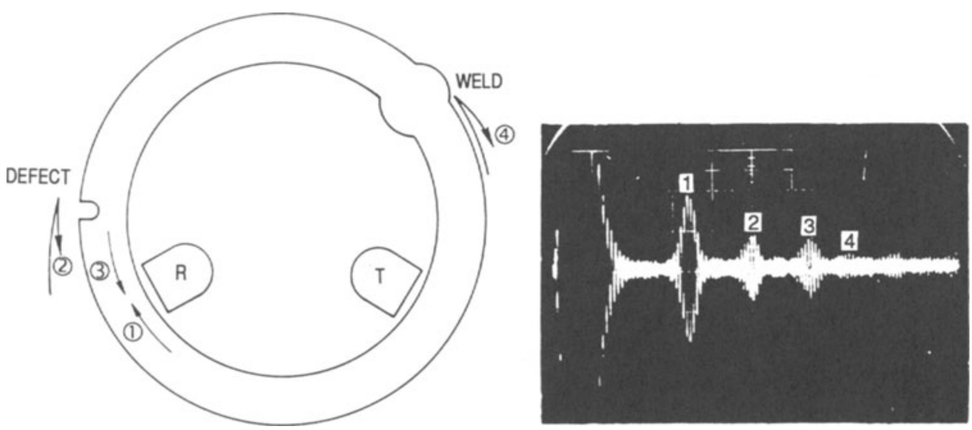


Figure 3. Guided mode signals in flawed and unflawed region of pipe.

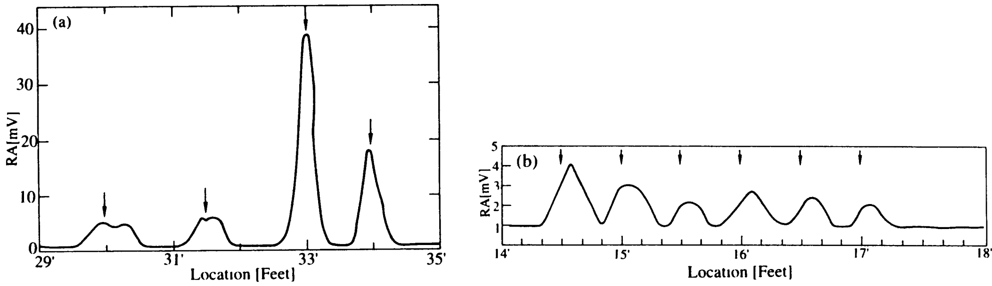


Figure 4. Waves reflected from machined defects: (a) slots; (b) flat-bottom holes.

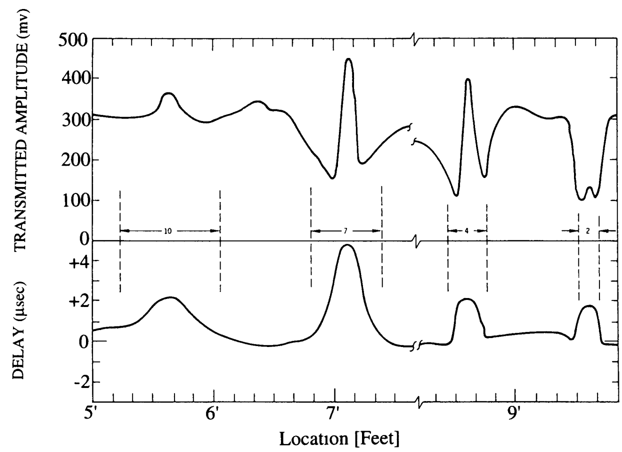


Figure 5. Effects of dish-shaped defects of transmitted sıgnals: Top: amplıtude; Bottom: delay.

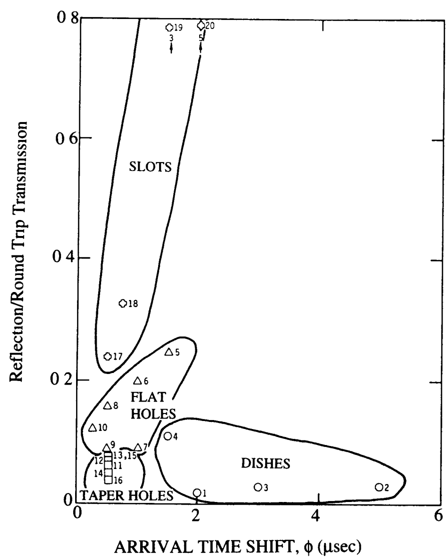


Figure 6. Classificatıon of different types of machıned defects based on comparison of amplıtude of reflected wave to time shift of transmitted wave.

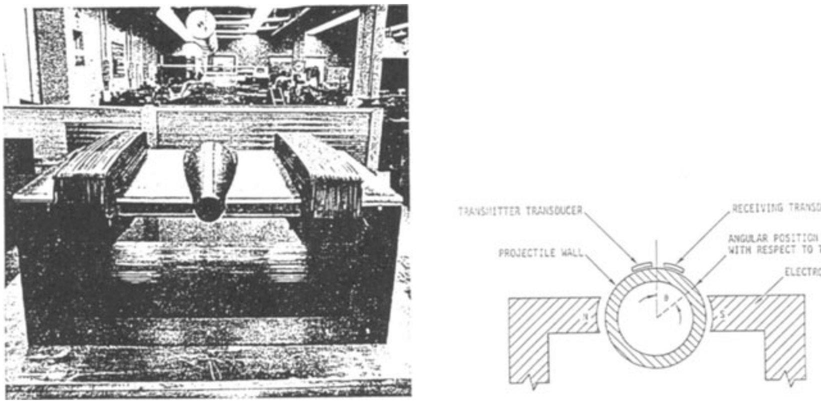


Figure 7. System for inspection of artillery projectiles

<u>Steam Generator Tubing</u>

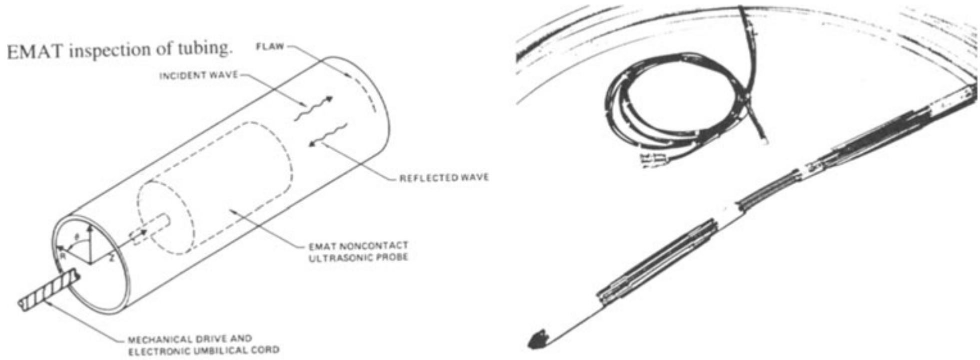
Under the support of the Electric Power Research Institute, an EMAT system was developed for the inspection of steam generator tubing in nuclear power plants [9-12]. Figure 8a illustrates the basic concept. An EMAT is inserted into the tube and used to excite guided modes propagating down the tube axis, with flaws indicated by reflections. The probe is attached to a mechanical drive and electronic umbilical cord which allows data to be gathered as it is pulled through the tube, much as in eddy current inspection. The SH-modes were chosen since these would be uninfluenced by the fluid in which the tubes were immersed because no leakage would occur.

Figure 9 illustrates the design approach The left portion shows that there are two families of torsional modes associated with various degrees of field variation around the circumference (quantified by the index m) and through the thickness (quantified by the index n) The right portion shows the dispersion curves for a particular steam generator tube, approximated by a flat plate with periodic lateral boundary conditions. It is evident that the thickness modes can easily be separated on the basis of frequency, but that separation of the circumferential modes requires considerably more finesse. The higher order circumferential modes can be suppressed on the basis of the circumferential profile of the tractions produced by the probe, but the design was complicated by the requirement that the probe be able to "telescope" sufficiently such that it could pass through a dent which reduced the diameter of a nominal 7/8 inch tube to 1/2 inch. Nevertheless, it was found to be possible to build a probe with four-fold symmetry (Fig. 8b) which achieved the necessary suppression. A step in the process was placing the wavevector of the m=4 mode exactly at the first null of the spatial Fourier transform of the aperture function.

The need to miniaturize the EMATs and to electrically couple to them through long lengths of cable had a deleterious impact on SNR. The signal observed in a single waveform was very noisy at the 350 kHz operation frequency of the n=0 mode. However, it was found that signal averaging improved this substantially, with further improvement afforded by matched filtering. A synthetic aperture techniques was also demonstrated to be able to achieve the benefits of signal averaging during probe motion through shifting the signals before averaging by an amount compensating for the shift due to probe displacement.

The n=0 modes were found to be very well behaved, being able to propagate over long lengths with low loss (on the order of a dB/foot) and around U-bends with little loss or distortion. Useful data was also obtained with the n=1 mode. However, in this case, dispersion caused a spreading of the pulses (and hence amplitude reduction) during propagation and the signals were strongly influenced by U-bends. Figure 10 compares the signal from a 40% deep transverse notch in short tube sections as seen with the two modes.

The sensitivity of the system to various types of defects was quantified by obtaining data on a Portable Tube Bundle of Inconel tubes containing circumferential flaws, pits, scallops, fretting, and erosion/corrosion defects. As would be expected on physical grounds, the greatest sensitivity was obtained for the circumferential (or transverse cracks). Figure 11 compares the sensitivity of the guided mode approach to the eddy current approach (circumferential coils) to this class of flaws, based on a second set of



(a) (b)

Figure 8. EMAT steam generator probe: (a) conceptual view; (b) photograph.

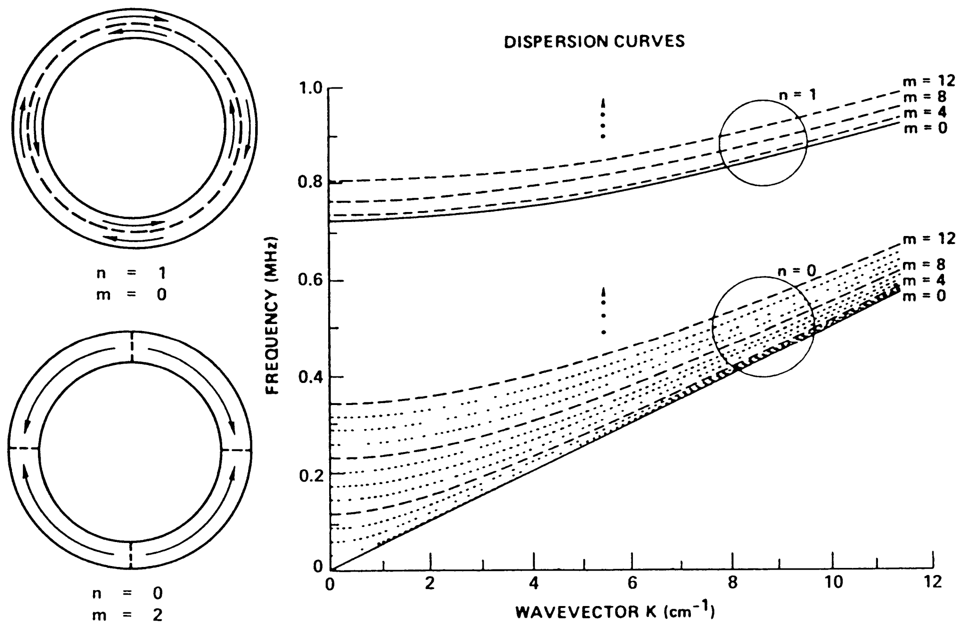


Figure 9. Modes of steam generator tubes.

measurements on a set of aluminum tubes, illustrating the superiority of the former. The situation is, of course, reversed for axial flaws, so that the two techniques can be viewed as complementary. Figure 12a shows the dependence of the flaw signal on defect area in the aluminum tubes, with flaws of the same depth indicated by the same symbol. The fact that the reflection coefficient is roughly proportional to area is evident and useful in sizing.

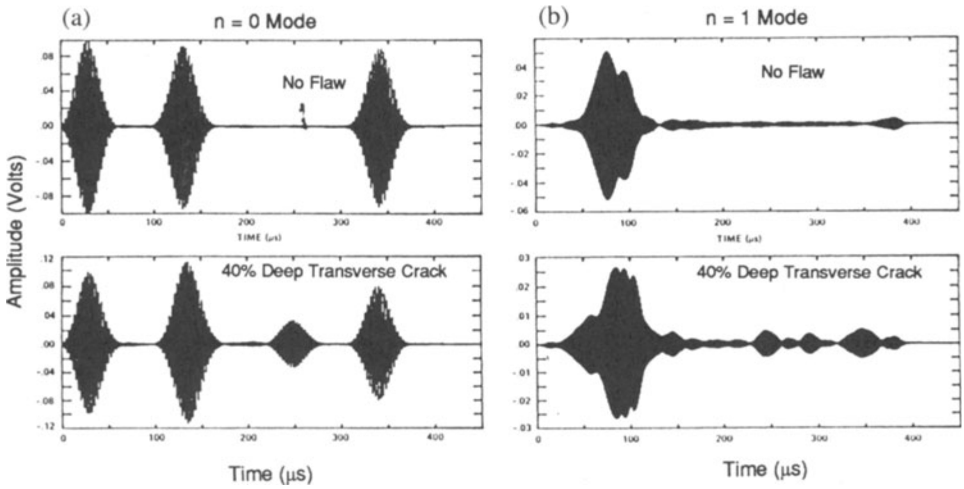


Figure 10. Signals from unflawed and flawed tubes: (a) n=0 mode; (b) n=1 mode.

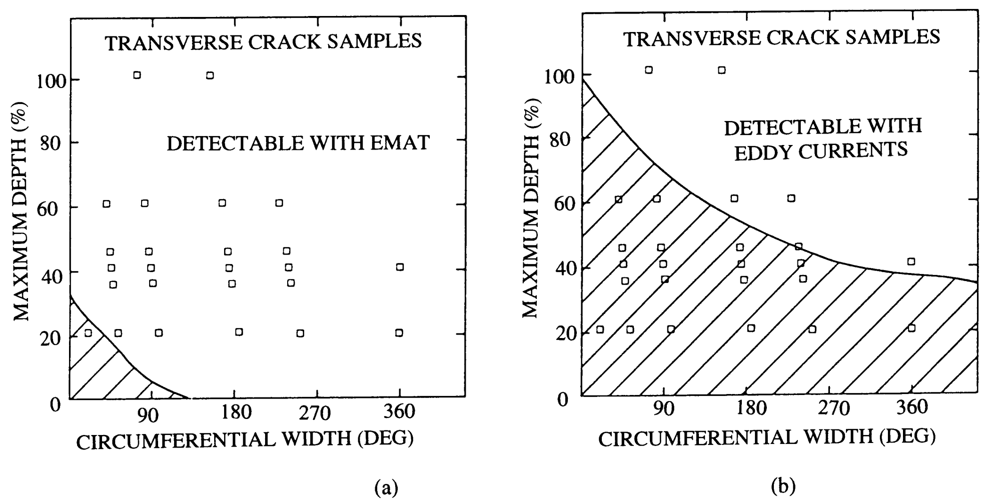
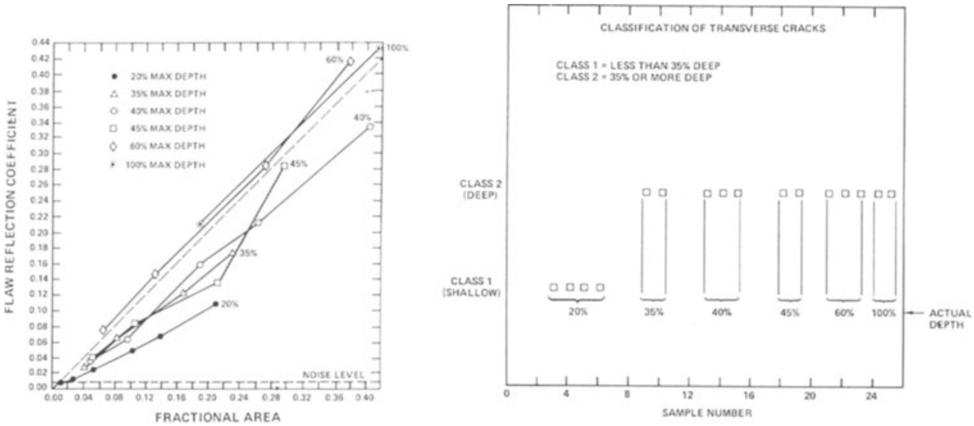


Figure 11. Detection of transverse flaws: (a). by SH guided modes; (b). by eddy currents.

An elementary flaw classification scheme was also developed based on the ratio of the reflections of the n=0 to the n=1 modes. The physical idea was that the strain energy of the n=1 mode is more concentrated near the surface (since there is a null of the displacement field in the mid-plane). Hence one would expect the reflection coefficient to increase less rapidly with flaw depth than it would for the n=0 mode, for which the strain energy is uniformly distributed through the wall thickness. Figure 12b illustrates the success of this approach.

CONCLUSIONS

Early application of guided modes to the inspection of buried natural gas pipelines, artillery projectiles, and steam generator tubes have been discussed. It was found that EMATs were a convenient way to excite and detect the modes because high mode selectivity could be achieved, traction directions could be adjusted to maximize efficiency, and, in ferromagnetic materials, magnetostrictive effects could be used to further enhance the efficiency. It was also found that a variety of parameters could be used to gain information about the flaws. Detection could be based on either the presence of a reflected signal or a shift in the amplitude or phase of a transmitted signal. Characterization could be based on the relative values of these parameters or on the relative responses of different modes.



(a) (b)

Figure 12. Flaw sizing and classification: (a) flaw signal versus flaw area for n=0 mode; (b) classification of depth of transverse cracks based on ratio of n=0 and n=1 reflection coefficients.

There are obviously trade-offs to made in the use of guided modes, not the least of which is that the rapid scanning of large or remote volumes precludes such techniques as focusing and hence limits sensitivity to small flaws. Wave attenuation or pulse distortion are other factors which can limit the volume scanned and, generally, the techniques used for flaw characterization are somewhat elementary as illustrated by the examples given above.

Nevertheless, there are many cases in which the advantages outweigh the disadvantages. The companion papers, describing many applications of current interest, provide ample examples.

ACKNOWLEDGEMENT

The work described above was conducted as a part of the contract research program of the Rockwell International Science Center in the period 1970-1980. Further detail may be found in the references. The work was the result of the efforts of many individuals, with key members being identified in the Introduction.

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