APPLICATION OF A FOURIER TRANSFORM-PHASE-SLOPE TECHNIQUE TO THE DESIGN OF AN INSTRUMENT FOR THE ULTRASONIC MEASUREMENT OF TEXTURE AND STRESS

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INTRODUCTION

This paper describes the development of an ultrasonic instrument to measure texture (preferred grain orientation), stress, and related physical properties in metal sheets in industrial environments. The technique is based on precise measurements of the speed of guided modes, including angular variations, and is made practical by the use of EMAT transducers, which require no couplant. The instrument is expected to find important initial applications in predicting sheet metal formability, either as a process control tool in the rolling mill or as a quality control tool in a stamping shop. Since the instrument will offer an improved measurement capability not presently available to industry, a much broader range of applications may develop, including measurements of stress and porosity in sheet and other simple geometries.

BACKGROUND

The texture (preferred grain orientation) of a polycrystalline metal sheet plays a key role in determining its formability [1]. For example, under conditions of large scale plastic deformation, one must be concerned about the ease with which this deformation occurs in different directions, information that is important in such operations as the formation of sheet into automotive bodies, airframe parts, and beverage cans. Engineering tests commonly used to predict formability include r-ratio measurements (ratio of in-plane to through-thickness plastic deformation in tensile tests) and earing tests (degree of scalloping of the rim of a cup formed by deep drawing). Considerable progress has been made over the last five years in utilizing ultrasonically obtained texture information in the prediction of these engineering parameters. Early studies concentrated on the predictions of formability parameters associated with drawing thin aluminum sheet into beverage cans [2]. This was followed by research in several countries aimed at predicting the average r-ratio (normal anisotropy) in steel sheet such as that used to automotive components [3-7]. The availability of an instrument based on these principles would allow one to implement process control procedures to control formability and thereby save material.

The principles underlying these techniques is the relationship between anisotropic elastic constants and preferred grain orientation. When the grains of a polycrystal are partially aligned, the ultrasonic wave speed will depend on propagation direction because of the anisotropy of the single crystal elastic constants. We have recently shown how to

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interpret this angular variation in terms of the orientation distribution coefficients, W_{lmn}, which define the texture [8,9], and a laboratory breadboard instrument has been developed [10,11]. In aluminum applications, the coefficients W_{420} and W_{440} are of greatest interest since they are related to the degree of earing that occurs during deep drawing to form beverage cans. In steel sheet applications in the automotive industry, W_{400} is dominant since it controls the average plastic strain ratio, $\bar{r}$, a crucial parameter in sheet metal formability analysis [12]. To determine the value of each of these parameters, one must know the speed of guided waves propagating at 0°, 45° and 90° with respect to the rolling direction of the sheet.

Measurement of stress in metal parts is also quite important. Deleterious consequences of improper stress levels range from catastrophic structural failure to undesired deformation during machining or service. X-ray diffraction technology can monitor stress, but due to penetration limitations, only a very near surface layer is examined. Ultrasonic approaches are sensitive to stress at greater depths. In essence, these techniques depend on a shift in the ultrasonic wave speed that is proportional to stress. However, the ultrasonic techniques have traditionally found limited application because of competing microstructural influences on the ultrasonic velocity. A recently developed procedure [13-16] has overcome that limitation. The solution rests on a measurement of the angular dependence of the velocity of shear waves whose propagation and polarization directions lie in the plane of a part surface. By taking the difference in the velocity of waves propagating in orthogonal directions, one can determine the stress, independent of microstructural considerations.

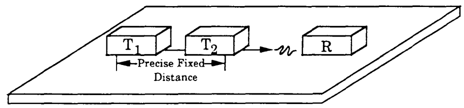
The key to practical application of these ideas is the use of couplant-free EMATs (electromagnetic-acoustic transducers) to excite and detect the ultrasonic waves [17]. The absence of a requirement for a couplant makes routine use on the shop or mill floor practical and opens the possibility of on-line operations in a real-time process control sense. Commercially purchased EMATs are incorporated in the aforementioned instrumentation projects. To this sensing capability must be added the capability for the rapid, automatic, and precise measurement of velocity. This paper describes the development of such a technique.

INSTRUMENTAL CONFIGURATION

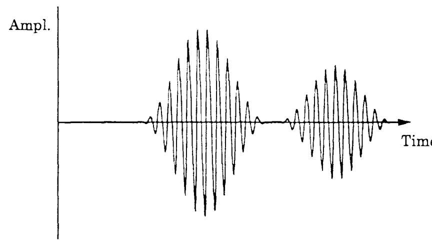
The plate wave velocity is derived from the difference in time of arrival of RF bursts using a T1-T2--R fixed array of EMAT transducers. In measurement of texture, velocities must be obtained oriented at 0, 45, and 90 degrees with respect to the rolling direction (the "1" direction). Stress is similarly measured, but requires only velocities of waves propagating in orthogonal directions. Figure 1 represents the T1-T2--R configuration and shows representative received waveforms from T1 and T2. The following diagram represents the modes of measurement and the magnet technology used in texture and stress prediction in the instrument under development.

	Texture (So Mode)	Stress (SHo Mode)	
Ferrous	0,45,90	0,90	Pulsed Magnets
Non-Ferrous	0,45,90	0,90	Permanent Magnets

The T1 and T2 EMATs are driven in series to eliminate differential phase shifts due to probe lift-off. A Fourier transform-phase-slope (FTPS) algorithm is used to determine the difference in time of arrival of RF bursts. Measurement cycle time is approximately 5-10 seconds depending on the type of measurements being made. Sampling period is 100 nanoseconds.



SHO EMATs on Plate Under Test



Received Waveforms from T_1 and T_2

Fig. 1. Time Measure Technique - By using two series driven transmitting EMATs in a fixed array with one receiver EMAT, Velocity is derived from the difference in time of arrival of the two waveforms.

From the measured velocity the average plastic strain ratio, $\bar{r}$, its anisotropy, Δr, and textural weights W_{400}, W_{420}, and W_{440} are derived for cubic crystallites. The instrument is capable of making measurements in sheet or plate of thicknesses up to 1/8 inch (3.175mm) having So or SHo velocities ranging from 0.19 to 0.67 cm/µs. The first instrument is restricted to cubic materials such as aluminum, copper, brass and steel. However it is possible to incorporate measurements on hexagonal materials such as titanium, zinc, and zirconium in future designs. Future designs could also accommodate greater thicknesses and other geometries.

FOURIER TRANSFORM-PHASE-SLOPE TECHNIQUE

The FTPS technique [18,19] is used to obtain an automatic, precise measurement of velocity. In its simplest implementation, one first computes the Fourier transform of the two received signals. The phase of the ratio of their transforms is then plotted versus frequency as shown in Figure 2. The slope is expected to be equal to $2\pi L/V$ where L is the propagation distance, thereby allowing the determination of the unknown velocity V. In our previous implementation of this technique, it was found that noise could easily induce tens of nanoseconds of error, which was more than could be tolerated in stress measurement applications. A detailed error analysis has been conducted to identify the source of this difficulty and to guide its resolution.

Fundamental Limits

We will first consider the fundamental limits in determining the relative arrival times of two noisy signals. This will then be used as a basis to discuss various implementations of the FTPS technique. The determination of the arrival time of a known signal, corrupted by noise, is a classical signal processing problem familiar to the radar and sonar communities. A Cramer-Rao lower bound [20,21] has been established, which states that the minimum variance σ_t^2 of time delay errors about the true time delay is

$$\sigma_t^2 \approx \frac{1}{d^2 B^2} \tag{1}$$

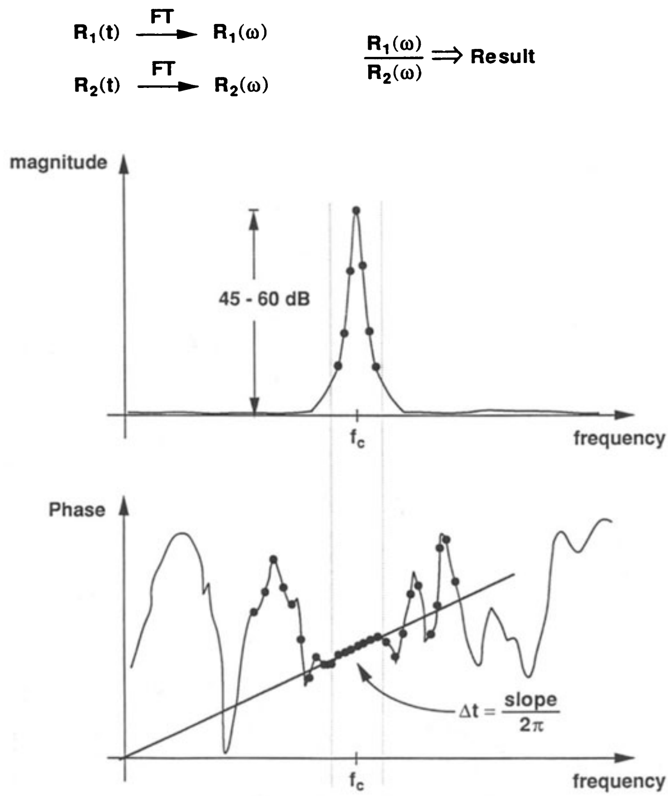


Fig. 2. Fourier Transform-Phase-Slope Technique for Estimation of delta-T.

where β is "a measure of bandwidth" and d^2 is the energy ratio of signal and noise in the pulse, equal to $2E/N_o$. Here, it is assumed that a coherent deterministic signal of total energy E has been corrupted by a white noise of constant spectral density, $N_o/2$.

For the narrow band tone bursts of interest here, examination of the definition of β shows that

$$\beta \approx 2\pi f_{o}, \tag{2}$$

β is thus determined by center frequency rather than bandwidth for a tone burst. If we define RMS_{noise} to be the rms value of the noise

then

$$N_o = (RMS_{noise})^2/W \tag{3}$$

where W is the noise bandwidth

and

$$d^2 = \frac{2W\int_{-\infty}^{\infty}|x(t)|^2 dt}{RMS_{noise}}. \tag{4}$$

where x(t) is the signal waveform.

Substitution of Eq. (2)-(4) into Eq. (1) yields the Cramer-Rao bound for a narrow band signal,

$$\sigma_t \approx \frac{1}{2\pi f_o} \sqrt{\frac{RMS^2_{noise}}{2W\int_{-\infty}^{\infty} x^2(t)dt}}. \tag{5}$$

If the time is to be determined by a digital signal processing algorithm, it is useful to convert Eq. (5) to a discrete representation. Suppose that the signal x(t) has been sampled at an interval δt. Setting the noise bandwidth equal to $(2\delta t)^{-1}$, as appropriate for the case in which the digitization introduces indepedent noise on each sample, Eq. (5) takes the form

$$\sigma_t \approx \frac{\sqrt{2}}{2\pi f_o} \frac{RMS_{noise}}{\sqrt{\sum_{i=1}^{N} x^2(t_i)}} \tag{6}$$

Here, a factor of $\sqrt{2}$ has been introduced to describe the case in which the relative time of a pair of noisy signals is to be estimated.

Analysis of FTPS Technique

Given this minimum variance as an ideal goal, the errors of the FTPS technique have been analyzed. Consider the sampled waveform with values $x(t_i)$ and noise of variance RMS_{noise}. After taking the discrete Fourier transform to obtain the discrete spectrum $x(f_i)$, it can be shown that the variance σ_p^2 in the phase angle at a particular frequency is given by

$$\sigma_p^2 = \frac{N(RMS_{noise})^2}{|x(f_i)|^2} \tag{7}$$

where N is the number of digitized time samples and $x(f_i)$ is the discrete Fourier transform of the signal. As would be expected, σ_p is smallest at those frequencies for which the signal spectra is strongest.

In the FTPS technique, a straight line is fitted through the points in a plot of phase versus frequency, with the delay being given by $m/2\pi$ where m is the slope. The accuracy of this time determination can be estimated from the accuracy of the regression analysis used to infer m from the data. This is most simply estimated if the variance is the same at each point. To obtain such an estimate, we consider a related problem in which the phase is only known at BT spectral points, where B is the original bandwith and $T = N\Delta\tau$ is the length of the originally digitized record. Estimating the average value of $x^2(f_i)$ over the bandwidth through application of Rayleigh's theorem leads to an expression for the variance in phase

$$\sigma_p^2 = \frac{2M(RMS_{noise})^2}{\sum_{i=l}^{N} x^2(t_i)} \tag{8}$$

Standard technique [22] can now be used to estimate the accuracy with which straight lines can be fitted through these points.

In simple regression, one fits a straight line through the points. After computing the variance in slope, one finds that the variance in estimate time delay, σ_t^2, is given by

$$\sigma_t = \frac{\sqrt{6}}{\pi B} \frac{RMS_{noise}}{\sqrt{\sum_{i=1}^{N} x^2(t_2)}}. \tag{9}$$

Comparison to Eq. (6) shows than, other than numerical factors, this is larger than the Cramer Rao band given in Eq. (6) by the ratio f_0/B. For the narrow band pulses excited by EMAT's, this ratio can be ten or more. This explains our unsatisfactory initial results with the FTPS technique.

However, we have found that considerable greater accuracy can be obtained when the regression line is forced to pass through the origin. Under these conditions, analysis of variance [22] leads to the expression

$$\sigma_t = \frac{1}{\sqrt{2}\pi f_o} \frac{RMS_{noise}}{\sqrt{\sum_{i=1}^{N} x^2(t_i)}} \tag{10}$$

This is identical to the Cramer-Rao bound. It is thus concluded that forcing the regression line through the origin is essential to achieving optimum performance with narrow band tone bursts. As the bandwidth increases, the forcing of the function through the origin offers less and less advantage.

In practice, the linear plot of phase versus frequency may have an intercept of any multiple of 2π due to the multiple solutions of inverse trigonometric functions. In order to select the correct multiple for the constrained regression, we use an unconstrained regression to first find the proper intercept, followed by a constrained regression in which the data is forced to pass through the selected multiple of 2π

Numerical simulations of the performance of this procedure have been performed with the results shown in Table I. In these simulations, a 500 kHz tone burst was sampled at a 100 nsec interval and Gaussian noise was independently added to each point. Despite the large sampling interval, time estimate accuracies on the order of one nanosecond have been achieved with noise representative of typical industrial environments. Figure 3 makes the comparison between the noise simulation data and the time error lower limit predicted by Cramer-Rao. Also shown is the result of an independent statistical estimate of the accuracy of the fit based on the actual data values [23].

SUMMARY

We have finished the design and development of a field prototype instrument to ultrasonically measure plate-wave velocity in rolled metal sheet and plate. From the measured velocity anisotropy, texture (preferred grain orientation), stress, and physical properties relating to formability can be derived. In order to achieve the reliability and accuracy required for the above mentioned measurements on a wide range of materials, several problems were solved. EMAT's were chosen because they require no couplant and are suitable for on-line applications such as process control. Permanent magnet EMAT's were selected for texture and stress measurements on non-ferrous alloys and magnetostrictive EMATs were chosen for ferrous alloys. Phase shifts due to lift-off have been reduced by driving the transmitter EMAT's in series. To make reliable wave-speed measurements in an industrial environment with an economical sampling period of 100 nanoseconds, a Fourier Transform-Phase-Slope technique has been implemented which achieves an accuracy approaching the Cramer-Rao bound.

Table 1. Simulated determination of δt between two RF bursts using FTPS technique. Each table entry represents a statistical ensemble of 10 trials at a given percentage of noise.

%Error+	Actual Delay	Predicted Delay (Mean)	Predicted Delay (Std Dev)
0.01	1.2E-5 sec	1.199999900E-5 sec	0.000000131E-5 sec
1	1.2E-5 sec	1.200009608E-5 sec	0.000018847E-5 sec
20	1.2E-5 sec	1.200025988E-5 sec	0.000222963E-5 sec
50	1.2E-5 sec	1.199487354E-5 sec	0.001049585E-5 sec
100	1.2E-5 sec	1.201095903E-5 sec	0.001641145E-5 sec
200	1.2E-5 sec	1.176823208E-5 sec	0.186305856E-5 sec
500	1.2E-5 sec	1.038405241E-5 sec	0.726061722E-5 sec

+ (RMN_{noise}/ Peak Signal)

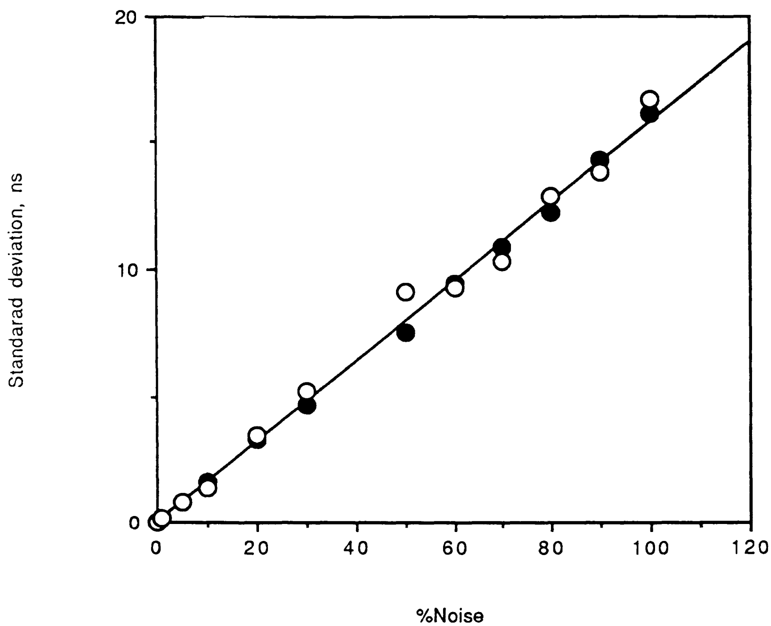


Fig. 3. Comparison of Cramer-Rao and Simulation Noise Data. Open circles represent simulation data points. Black circles are the error limit estimates predicted by Cramer-Rao.

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