MEASUREMENTS OF LONGITUDINAL-WAVE VELOCITY IN IIW-TYPE CALIBRATION BLOCKS *

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INTRODUCTION

IIW-type (International Institute of Welding) ultrasonic calibration blocks are used widely throughout the world in nondestructive testing of materials and structures. They are used to establish certain physical characteristics of ultrasonic search units (transducers and plastic wedges) and flaw detection systems. Figures 1a and 1b illustrate the geometries of the two popular U.S. variations of the IIW-type block: IIW-Type 1 design referenced by ASTM (American Society for Testing and Materials), and IIW-Type 2 commonly known as the U.S. Air Force design. The blocks are nominally 300 mm (12 in.) long, 100 mm (4 in.) wide, and 25 mm (1 in.) thick. The geometry, physical characteristics, and uses of the ASTM design are specified in the ASTM standard E-164, while the Air Force design is described in the U.S. Air Force Technical Manual on Nondestructive Inspection Methods. A comprehensive summary of the different block designs and physical characteristics is given by Hotchkiss [1].

Figure 1a. ASTM IIW-type ultrasonic calibration block.
Figure 1b. U.S. Air Force IIW-type ultrasonic calibration block.

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A proposed European standard, prEN 12223:1995, describes the current European design of the IIW-type block. The International Organization for Standardization (ISO) is considering adoption of this proposed standard in its current form. The proposed European standard specifies that the longitudinal-wave velocity of the block be measured within ±0.1%, or ±6 m/s, assuming that the block is made of a low-alloy, EN 10025-type steel (1025 steel in the U.S.) with a nominal longitudinal-wave velocity of 5920 m/s. In contrast, the current ASTM standard on ultrasonic velocity measurements in materials (ASTM E-494) states that the longitudinal-wave velocity can typically be determined with only a 1% uncertainty for relative measurements, and a 5% uncertainty for absolute measurements. Other differences between the proposed European standard and ASTM standard exist and are significant. The proposed European standard specifies that the longitudinal-wave velocities of the total population of steel IIW calibration blocks used by the European NDT service community "shall be within 5920 ±30 m/s." The corresponding ASTM standard does not specify a tolerance on material velocities in the IIW-type block because a consensus among its voting membership could not be reached. To help harmonize the European and ASTM standards, ASTM subcommittee E-07.06 asked the National Institute of Standards and Technology, as an independent group, to make velocity measurements in steel IIW-type calibration blocks, assist in setting appropriate tolerances for the blocks, and recommend revisions in the suggested measurement methods.

In this paper, we describe the geometry of the experimental method (pulse-echo), the set of IIW-type blocks used in the study, and the experimental method used to determine the velocities of the blocks (time of arrival). We briefly review two time-of-flight techniques used to determine the longitudinal-wave velocities. We also discuss the known errors affecting our velocity measurements and the uncertainties associated with the measurements. We then state the experimental results, analyze these results and formulate appropriate conclusions regarding the feasibility of the proposed European standard.

EXPERIMENTAL METHOD AND GEOMETRY

The longitudinal-wave velocities of the blocks were obtained by dividing the distance traveled by the ultrasonic pulse in the block by the measured transit time. The thickness of each of the blocks was measured with a micrometer capable of ±0.0025 mm (±0.0001 in.) at a number of different locations and averaging the measurements. Two time-of-flight techniques were used to measure the time delays: the well documented Pulse-Echo Overlap (PEO) method, as described by Papadakis [2-4], and the First-Arrival-Superposition Technique (FAST), which we developed during the course of this study. FAST is a refinement of a technique described earlier by Eros and Reitz [5]. Both techniques were implemented using commercially available transducers, analog and digital instrumentation, and signal analysis techniques. The experimental geometry is depicted in Figures 2 and 3, where a pulse-echo arrangement through the thickness of the block is shown.

SAMPLES

The sample set of IIW-type calibration blocks being used in our study consists of 16 blocks, labeled 'A' through 'P'. The sample set includes blocks of different age, origin, composition, and design. We believe some of the blocks were made from recently processed steel (<5 years ago), since these blocks were obtained directly from current calibration block suppliers. We suspect the others were made from steels processed during earlier steel manufacturing eras (>20 years ago), and therefore most likely contain different microstructures than those more recently processed. The exact ages of most of the blocks
are not available and could only be estimated from supplier markings permanently stamped on the blocks. All of the blocks are on loan to us from U.S. companies or U.S. citizens, and we believe that all of the blocks were manufactured in the U.S. The chemical composition of most of the blocks was well documented by their owners, with the majority of blocks being 1018, 4340, or A36 low-alloy steels. However, the composition of some of the blocks is unknown.

TIME-OF-FLIGHT MEASUREMENTS

As mentioned earlier, we selected two time-of-flight measurement techniques to determine the velocities of the blocks: the PEO and FAST methods. The PEO method was selected because it is frequently used in highly accurate laboratory determinations of elastic wave velocities and can determine these wave velocities to within a very narrow range of uncertainty. The FAST method was selected and refined since first arrival techniques can be easily used in field applications. The PEO measurements were used to establish our best estimates of the block velocities, allowing us to determine how well the measurements made by the FAST method compare to the PEO measurements.

Superficially, the two techniques are very similar in that they both rely on the superposition of successive time waveforms due to back-wall reflections. However, their conceptual origins are considerably different. PEO makes use of narrow-band signals, while FAST is inherently a broadband technique. Also, different features of the waveform are utilized in the superposition process. The PEO method overlaps a number of individual cycles in the tone burst, while the FAST method overlaps just the first arriving portions of the waveforms.

For the PEO method, a function generator supplied a 16 V zero-to-peak, sinusoidal tone burst of a single frequency to a 12 mm diameter, 5 MHz lithium niobate transducer, as shown in Figure 2. The number of cycles included in the tone burst was 20. A tuning component, consisting mainly of an inductor, was inserted between the function generator and transducer to impedance match the two components. A special coupling fixture was developed and used to guarantee excellent electrical connections between the transducer and the rest of the circuit. The transducer was carefully bonded to the block surface with phenyl salicylate as specified by Papadakis [2]. The room temperature during the bonding process and measurements was approximately 21 °C. After the bonding procedure was

![Figure 2. Apparatus used for the PEO measurement technique.](image)
completed, the transducer then transmitted the ultrasonic waves in the 25 mm (1 inch) direction of the block. The transducer received these multiple back surface echoes, which were amplified by a broadband receiver, with gains typically set between 10-14 dB. The amplified signals were displayed on an oscilloscope, averaged 20 times, and stored in computer memory for later analysis. For steel IIW-type blocks, typically only the first and second back surface echoes had adequate signal/noise ratios for proper signal analysis. Once the wave train containing the first and second back surface echoes was stored in computer memory, the wave train was replicated and visually displayed through the use of appropriate software. The first and second back surface echoes were then digitally overlapped, and through the use of the McSkimin $\Delta T$ Criterion [6,7], the correct cycle overlap of the multiple cycle tone bursts was determined. Once the correct cycle overlap was identified, the measured time delay was found. Using a procedure described by Papadakis [3], the time delay was corrected for bond and diffraction effects. The corrected time delay was used to determine the longitudinal-wave velocity of the material.

The FAST method superposes the back surface echoes in a similar manner to the PEO method. However, with the FAST method, we are focused only on the correct overlap of the first arrivals of the signals, and not the entire waveforms, since the earliest arrival of the signal will most likely be the part of the signal least corrupted by material effects such as dispersion and attenuation. Currently, no corrections are made for the internal structure of the transducer (housing, wear plate), diffraction effects, or the couplant layer between the transducer and the block. While it is the structure of the transducer and the use of liquid couplants that make this type of measurement possible in practical situations, it is these very factors that introduce the most error and uncertainty to the experimental measurements and resulting velocity estimations.

For the FAST method, a pulser supplied a square wave pulse with an amplitude of 50 V and pulse duration of 120 ns to a PZT transducer via a standard diplexer, as shown in Figure 3. Approximately 200 g of mass was placed on top of the transducer to provide a uniform and constant source of pressure in order to establish consistent contact between the transducer and the block. A thin layer of glycerin was used to couple the transducer to the block. The transducer transmitted an ultrasonic pulse through the 25 mm thickness of the

![Figure 3. Apparatus used for the FAST measurement technique.](image-url)
block and received the multiple back surface echoes reverberating within it. A broadband receiver then amplified the multiple reflected pulses with typical gains of 0-4 dB. A digital oscilloscope was used to display the amplified pulses. The displayed signal was a single shot - no averaging was necessary. The received pulse train was stored in computer memory for later analysis. As with the PEO method, only the first and second back surface echoes were used by the FAST method to determine the time delay. With the received pulses stored in computer memory, a software program was used to copy and overlap the first back surface echo on top of the second back surface echo. By visually aligning the first arrivals of both signals, a time delay between the two echoes was measured.

ESTIMATIONS OF UNCERTAINTY

The value of a physical property deduced from experimental measurements must never be considered the “true” value of that property; it is, at best, an estimate of the quantity taken under those particular experimental conditions. It becomes necessary to first identify and, if possible, correct the measured value for any known errors introduced by the measurement process. The quality of the measurement can then be described in quantitative terms by assigning an uncertainty value to it. Errors in measurements are typically categorized into two classes: errors due to random effects, and errors due to systematic effects. It is possible to estimate the magnitude of an error due to systematic effects and correct the original measurement value, although there will always be some uncertainty present in the estimate of the error and in the resulting corrected measurement value. It is not possible to compensate for errors due to random effects. We can only hope to reduce the uncertainty associated with the random effects by increasing the number of repeated measurements we make on the specimen, and then averaging the measurements. Uncertainties may be further classified as being due to application factors or human factors.

Both measurement techniques are affected significantly by systematic errors due to application factors. The narrow-band pulse used in the PEO method makes it possible to estimate systematic errors due to bond thickness and ultrasonic beam diffraction. These systematic errors are usually quite small, each shifting the uncorrected velocity by no more than 10 m/s. The estimated uncertainty associated with each of these systematic errors is ±5 m/s. Due to the characteristic broadband pulse of the FAST method, it is not currently possible to estimate the systematic errors affecting this technique. However, we are able to estimate the uncertainty introduced to the FAST measurements by systematic errors such as diffraction and the presence of a wear plate on the transducer. The uncertainty due to diffraction is estimated to be ±35 m/s, while the uncertainty due to the wear plate is estimated to be ±71 m/s.

Random uncertainties in the time-of-flight measurements of both measurement techniques are due to mainly signal processing factors (application factors), such as the signal/noise ratio, quantization resolution, and sampling rate. The random uncertainty due to these quantities is estimated to be ±2 m/s for the PEO measurements and ±17 m/s for the FAST measurements.

The main uncertainty in the PEO time-of-flight measurements due to human factors is the visual overlap of the first and second back surface echoes. The visual overlap process is critical for estimating the elapsed time of travel between the two pulses. As expected, there will be some ambiguity as to which elapsed time overlaps the two echoes most accurately. However, much of the random error introduced by the operator’s choice of overlap position can be reduced significantly by overlapping a subset of individual cycles in
the burst and averaging their individual elapsed times. We have typically averaged over the last 10-12 cycles for signals consisting of a 20-25 cycle tone burst. We have found that while different operators will record different elapsed times for individual cycles, their averages over that same subset of cycles are remarkably similar, and the resulting uncertainty is negligible when compared to the other sources of uncertainty.

As with the PEO measurements, the main uncertainty in the FAST time-of-flight measurements due to human factors is the visual overlap of the first and second back surface echoes. The signal-to-noise ratio becomes particularly critical for this type of measurement since distinguishing the true first arrival portion of the wave form from the noise for both the first and second back surface echoes is very important for accurate time-of-flight measurements. If the signal-to-noise ratio is not excellent for both back surface echoes, then there is a great opportunity for subjective interpretation during the overlap procedure of the signal analysis portion of the measurement.

EXPERIMENTAL RESULTS

A number of measurements were made on each block using the FAST method. Four researchers used the same three transducers to make the measurements, resulting in a total of 12 measurements for each block. Transducers used in this study were all nominally 12 mm in diameter. The center frequency of two of the transducers was nominally 5 MHz (one impedance matched for steel, the other for plastic), while the third was 2.25 MHz (impedance matched for steel). The pulser, receiver, and oscilloscope settings were fixed for each block. The use of various transducers and people making the measurements was an attempt to mimic a practical environment, since different NDT inspectors will use different types of transducers in their actual inspections. Errors and uncertainties directly attributable to the use of different types of transducers and different operators will be reported in a future paper. Only the final uncertainty estimations are reported here.

Longitudinal-wave Velocities Using FAST

Figure 4. The mean velocities of each IIW-type block obtained with the FAST method. Minimum and maximum velocities are shown as error bars.
The longitudinal-wave velocities measured in the 25 mm direction of the blocks with the FAST method are displayed in Figure 4. The mean value for the 12 measurements made on each block is displayed along with the minimum and maximum values, shown as error bars in the figure. The total uncertainty for each of the velocity measurements is estimated to be ± 80 m/s. The brackets in the upper right hand corner of the figure indicate the proposed tolerance of ±6 m/s stated in the European draft. As can be seen, the variations between the maximum and minimum velocities exceed the proposed tolerance of ±6 m/s.

The velocity measurements determined using the PEO method are shown in Figure 5 along with the averages of the FAST measurements. The estimated uncertainty of the PEO measurements is ± 8 m/s. With the exception of block ‘O’, the averages of the FAST measurements are all lower than the PEO velocity measurements. Since the PEO values are adjusted for systematic errors due to bonding and diffraction, these measurements are a more accurate estimate of the “true” velocities of the blocks. We would expect to see a certain amount of bias in the FAST measurements since they are not corrected for systematic errors. We suspect the systematic errors in the FAST velocities are the reason why the FAST averages are consistently lower than the PEO velocities shown in Figure 5.

CONCLUSIONS

The velocity measurements presented in Figures 4 and 5 now allow us to address the feasibility of achieving two of the proposed tolerances stated in the European draft. It is clear that all of the blocks, with the possible exception of block ‘A’, would be acceptable reference blocks based on the criterion that the blocks have longitudinal-wave speeds of 5920 ±30 m/s. The PEO measurements all fall within this acceptable range, with the exception of block ‘A’, as do the mean values of the FAST measurements. However, with the estimated uncertainty of the FAST measurements being ±80 m/s, little confidence may be placed in any conclusions based only on these measurements. The situation is further complicated by the fact that different operators used different transducers when making the FAST measurements, i.e. the measurement process did not remain constant. Further

Summary of Longitudinal-wave Velocities

Figure 5. Comparison of the PEO measurements with uncertainties of ±8 m/s and the mean values of the FAST measurements with uncertainties of ±80 m/s.
statistical analysis is needed to estimate the individual systematic errors due to the different operators and different transducers.

Determination of the longitudinal-wave velocity to within a ±0.1% (± 6 m/s) tolerance is not practical or reasonable when conventional NDT-type transducers and signal analysis techniques such as the FAST method are implemented. As seen in Figure 4, the variance between the minimum and maximum velocities measured on each of the blocks exceeds the proposed tolerance of ±6 m/s. Uncertainties in these types of measurements are estimated to be on the order of ±80 m/s, where the majority of this overall uncertainty is due to systematic errors like diffraction and wear plate effects, which currently cannot be corrected for. If only random errors are considered, then the uncertainty due to imprecision reduces to ±17 m/s, which is still three times as great as the proposed ±6 m/s, implying that the measurement process itself is unable to reach uncertainties of ±6 m/s.

However, the 0.1% tolerance on longitudinal-wave velocity measurements seems viable when the Pulse Echo Overlap method is used. The effects of systematic errors due to bond thickness and diffraction can be reduced through theoretical corrections. The major drawback of this measurement technique is the extensive amount of time and technical expertise needed to make the measurement properly. While it has been proven to work very well in the laboratory environment, it is not economical or practical to require field inspectors to implement it in a practical environment.

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REFERENCES