Image Processing for Accurate Sizing of Weld Defects Using Ultrasonic Time-Of-Flight Diffraction

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Abstract. Ultrasonic Time-Of-Flight Diffraction (TOFD) is rapidly gaining prominence as a reliable non-destructive testing technique for weld inspection in steel structures, providing highly accurate positioning and sizing of flaws. It's use as a rapid non-destructive inspection tool for steel plates, pipelines and vessels has grown tremendously during recent years, brining into light the challenge of developing a fast and reliable data processing and interpretation platform. Although the data acquisition configuration lends itself conveniently to automation, and methods such as robotic scanning and computer-conditioned data acquisition are routinely used, the crucial processes of data processing and interpretation are still performed off-line manually depending heavily on the skills, experience, alertness and consistency of the trained operator. Results typically suffer from inconsistency and errors, particularly when dealing with large volumes of data. A number of signal and image processing tools have been specifically developed for use with TOFD data and adapted to function autonomously without the need for continuous intervention, configuring automatically according to the nature of the data and the data acquisition settings. This paper presents the results of several innovative procedures developed and implemented for the automation of the sizing and positioning of weld flaws in TOFD data as an essential stage of a comprehensive TOFD inspection and interpretation aid. This automates the sizing process, generating a quality appraisal of a scanned weld, detailing the location and geometry of all detected flaws.

Introduction

Non-destructive testing (NDT) is commonly used to monitor the quantitative safety critical aspects of manufactured components and goods and forms one part of the quality assurance procedure. In the 21st century, the strategic trend in the development of NDT has changed towards the issue of safety in the broadest sense, to the protection of the population and the environment against man-made and natural disasters and the safety of the public is now a basic engineering principle. Industrial NDT of manufactured items is usually undertaken when a product is likely to be placed under extreme or long periods of stress or wear, or if any component failure is liable to result in a major incident.

For applications such as the inspection of welded joints in steel structures, ultrasonic techniques are still generally the NDT method of choice. TOFD is one such ultrasonic technique developed by Silk [1] in the late 1970's to improve the sizing accuracy of flaws. Because of the limitations of achieving accurate sizing and positioning from D-scan presentation of TOFD data, both the manual and the automated trials [2, 3, 4, 5, 6] were carried out on B-scan representations of TOFD data. All these attempts for automatic sizing and positioning are mainly based on using B-scan representations of TOFD data, which essentially add no further accuracy to what the expert operator could have achieved manually. This paper presents the results of the developed novel signal and image processing to overcome the limitations of achieving accurate sizing and positioning using D-scan presentation of TOFD data which can not be achieved using manual sizing, and demonstrates how it would fit into a comprehensive automatic processing and interpretation system. This comprehensive interpretation aid for TOFD data using D-scans has been developed and implemented [7], with emphasis on accuracy, reliability, efficiency, minimum user interaction and simple output presentation in order to be suitable for in-site interpretation, thereby shifting part of the interpretation burden from the trained operator to the computer.

Why Accurate Sizing?

Most modern forms of transport and industrial equipment rely on the integrity of steel components with welded joints which are directly or indirectly subjected to large and rapidly varying stresses. When failure occurs, it is often because the component contained a defect. Such defects may arise from faulty manufacture or the effects of service in a corrosive environment and may be enlarged by fatigue. Even very small crack-like flaws can very quickly be enlarged by fatigue and cause a major reduction of strength leading to catastrophic failure of the structure. This failure can occur by rapid brittle fracture if these flaws exceed a certain critical size for the load applied [8]. Therefore, accurate measurement of the through-wall extent of the flaws has great importance in ensuring the structural integrity of many structures by detecting the defects that could trigger such a failure. Ultrasonic NDT techniques are commonly used to detect and size these flaws both pre-service and in-service.

TOFD

Conventional ultrasonic techniques, such as pulse echo, measure the reflected pulse transit time and the signal amplitude to locate and size flaws. As the amplitude of the reflected pulse is influenced by parameters other than the dimensions of the reflector (such as the orientation of the flaw, transparency and surface roughness); pulse-echo may not always provide reliable or accurate sizing information. Echo strength in TOFD on the other hand, does not depend on the flaw orientation, allowing flaw sizes to be accurately determined (generally accurate to within ±2% of wall thickness, typically less than ±1mm), with a high probability of detection of approximately 95%.

Flaw sizing using TOFD depends on the accurate measurement of arrival time of the diffracted and reflected waves at the flaw extremities. Two longitudinal broad beam probes are used in a transmitter-receiver arrangement, so that the entire flaw area is flooded with ultrasound and, consequently, the entire volume is inspected using a single scan pass along the inspection line, as shown in Figure 1. The collected data can be visualised in an A-scan representation or stacked together side-by-side in a raster representation called a D-scan (longitudinal) or B-scan (parallel) depending on the relative scanning direction.

Initial-processing and Defect Detection

Initial processing is required before the process of defect detection and subsequent sizing and positioning. This stage involves noise suppression, drift correction, scan alignment and the estimation of lateral wave and backwall signals positions [9]. After automatic estimation of the positions of lateral wave and backwall signals, the defect detection process is carried out only in-between the two. Accurately outlining and highlighting those areas of interest, and labelling them as likely defect zones is essentially an image segmentation process [9], and permits more exhaustive image/signal processing to be carried out in subsequent sizing and positioning. Sizing of these defects then proceeds using these regions of interest only.

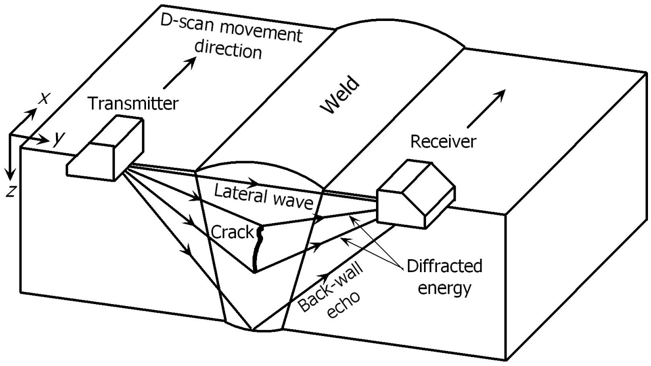

Figure 1. Illustration of TOFD operation

Flaw Sizing

The arrival times of the diffracted wavefronts carry information about the spatial relationship of the crack tips and hence the height and depth of the flaw can be estimated from the accurate measurements of the arrival times of these echoes compared to those of the lateral wave and backwall echo. The positioning of the tip signals can then be used to derive information about the actual flaw depth and height.

Similar to the lateral wave and backwall echo, returns from the upper and lower extremities are expected to be 180° out of phase: echoes diffracted from the flaw bottom are approximately in-phase with the lateral wave, whereas those diffracted or reflected from the flaw top are approximately 45° out of phase with the backwall echo. Correct exploitation of this phase information adds accuracy to the subsequent sizing and positioning [10]. Taking the above phase information into account allows accurate determination of the exact positions in time for the upper and lower extremities as well as the relative times between these and the upper and lower surfaces as shown in Figure 2.

The size of the flaw is determined by its width and height, with width defined as the difference of the flaw extremities in the ***x*** (lateral) direction, while height is defined as the maximum difference of the flaw extremities in the ***z*** (through-wall) direction. A further parameter, depth, is defined as the difference between the scanning surface and the flaw top extremity in the ***z***-direction. The position of the flaw is thus determined by its depth and its distance from the scanning start point.

The height of the flaw is directly determined from the difference between the depths of the top and bottom echoes of the flaw while the depth is the distance between the scanned surface and the upper extremity of the flaw, which in practice is directly related to the time between the lateral wave and the echo from the flaw's top tip, taking into account the phase relationship between the two signals. Due to the nature of such flaws, the signatures of the top and bottom echoes are usually inflated and suffer from profile variations. Therefore, in order to accurately size any flaw, the detection of the profile of flaw top and bottom envelopes is achieved by successive sub-sampling and cross-correlation as shown in Figures 3. From the obtained profiles for the top and bottom tips of the flaw in addition to estimation of lateral wave time, the minimum and maximum height and depth can be accurately extracted automatically.

The width of the flaw can be estimated directly from the width of its record on the D-scan, but this record is usually elongated due to the finite width of the ultrasonic beam. There will be hyperbolic ``wings" at the ends of the flaw record generated when the probes approach and leave the flaw. This elongation reduces the accuracy of the width estimation to about ±5 mm. This elongation is treated here by automatic detection and fitting a curve to the wings of the defect record in order to estimate their start points and then eliminate their effect on width estimation. As a result, the defect width can be accurately estimated without the error introduced by the added width of the wings, greatly reducing the effect of the elongation on the width estimation.

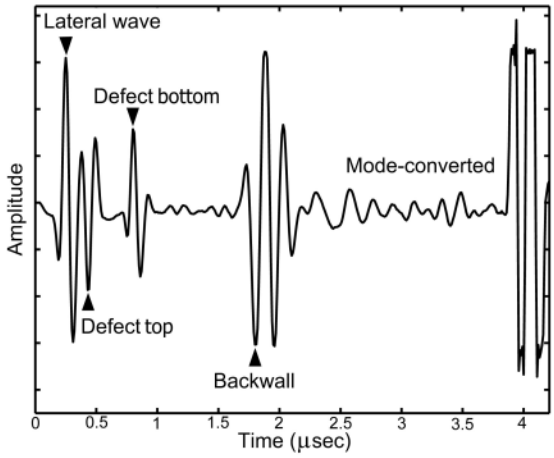

Figure 2. Wavelet positions illustrated on an A-scan of an internal crack

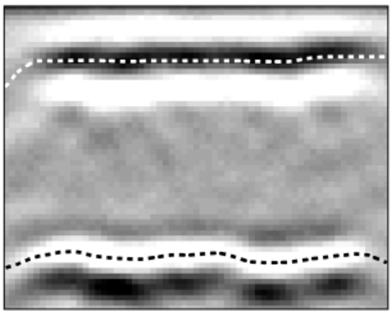

Figure 3. Detection of top and bottom profiles of detected flaw

Sizing Limitations and Minimising Errors

The accuracy of a TOFD-measurement is influenced by a combination of errors resulting from probe centre separation uncertainty, timing uncertainty (from probe delay error and phase measurement errors), and uncertainty in lateral position of the defect, in addition to the errors in the estimation of the sound propagation velocity. The procedures developed to overcome these limitations are:

1) Estimating the effective value of probe centre separation by calibrating the measurements on a signal with a known depth making use of the specimen thickness and

the (accurately known) lateral wave and backwall times (which are previously measured in the initial processing stage [9]).
2) Reference all time measurements to the lateral wave time which is identified automatically in the initial processing stage [9].
3) Successive detection and tracking of peaks and troughs within the defect window and determining their exact positions in time for each scan taking into consideration the relative phase relationship between the two wavelets.
4) Correcting the phase difference automatically in depth calculation by subtracting the time equivalent to the phase difference from the time of the tip echo.
5) Correct the measured width automatically by eliminating the effect of elongation, by estimating the start point of the wings generated at the ends of defect profile.
6) Correct the lateral position of the defect using curve fitting of the wings generated at the ends of defect profile.

By overcoming these limitations, sizing errors will be minimised and hence TOFD can be equally applicable to the search for flaws in D-scans and to accurate flaw sizing.

Post-processing

All sizing and positioning results are related to measurements in the image domain and not to the actual depth and length of the flaws themselves. The horizontal axis is in the spatial domain whereas the vertical axis represents time. A post-processing is needed in order to obtain the final interpretation output in the actual sizing and poisoning measurements. The post-processing starts by rescaling the vertical axis from samples or pixels to seconds and then expresses depth. The vertical axis is rescaled to represent depth while the horizontal axis is rescaled to the actual scanned distance in millimetres. The dimensions and depths previously computed for each defect are thus automatically re-scaled to units of length. The adopted acceptance criteria and reporting codes are applied based on these measurements in order to generate a final report. The reported final interpretation results indicate the depth, height, width, and distance from scanning start-point.

Results

The developed procedure has been applied to a data set consisting of 76 D-scans containing 150 defects. These defects are all characterised and documented by the manufacturer of the steel plates, and independently verified by a trained expert. The majority of achieved results are more accurate than the manual results, referring to the data sheets of the scanned plates, while only around 11% are the same as measured by a trained operator. For flaw depth measurements, the error is within ±1mm, for all defect classes except for the surface breaking crack where the error is within ±2mm because as described earlier, one echo is merged with lateral wave or backwall echo. For flaw height measurements, the error is within ±1mm, for all defect classes except for the surface breaking crack where the error is within ±3mm. For flaw width measurements, the error in the majority of cases is within ±1mm, but for some cases it is within ±3mm.

The developed sizing and positioning procedure has proven to be rapid, accurate and robust as the results are very accurate compared to manual sizing and positioning by a trained operator but in a fully automatic and unsupervised manner. Sizing and positioning process has been achieved in a matter of seconds for each image, using a 1.5GHz PC running Matlab^{TM} which considered as a great achievement as from simple D-scans. The final data display is more readily understood by people not routinely involved with ultrasonics as shown in Figure 4.

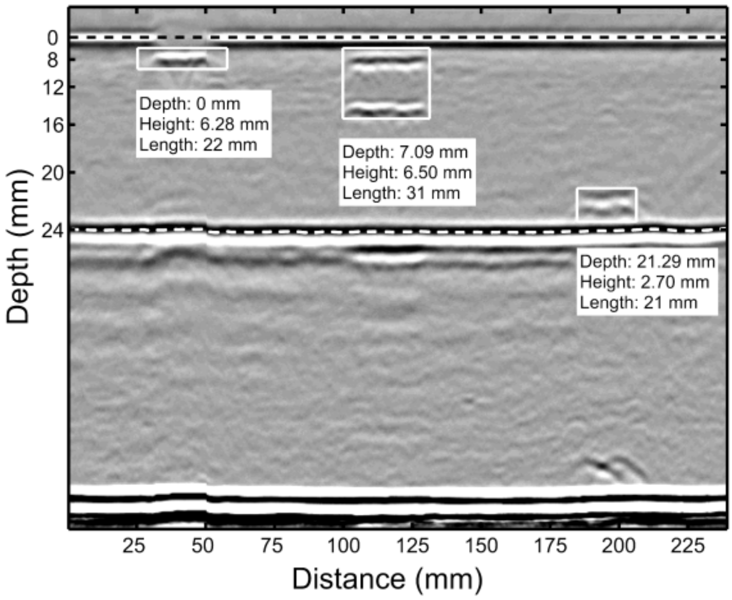

Figure 4. Final sizing output representation indicating sized flaws

Conclusions

This paper has addressed the task of automatic sizing and positioning of detected defects in ultrasonic TOFD data as part of a comprehensive automatic interpretation aid. A number of signal and image processing techniques have been developed to overcome the sizing limitations and their associated errors, resulting in a batch weld appraisal system where defects are automatically detected, positioned and sized prior to the expert's inspection, relieving the operator of the more mundane and routine tasks.

All processes are carried out automatically, with parameters configured directly from the data itself and the data acquisition settings, avoiding the need for any external intervention in the processing, and allowing batch file processing.

Results of the application of these techniques to the available data have been extremely promising in terms of speed, robustness, accuracy and reliability when dealing with highly variable data. This would make the proposed system suitable for implementation in situations requiring near real-time processing and interpretation of large volumes of data, and thus these techniques are expected to greatly reduce the possibility of human and experimental error, due to loss of concentration and visual fatigue, and the reliance on intervention from a trained operator, and could potentially open a new paradigm in TOFD for automatic interpretation.

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