Non-destructive testing — Ultrasonic testing — General use of full matrix capture / total focusing technique (FMC/TFM)
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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO’s adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by the IIW, International Institute of Welding, Commission V, NDT and Quality Assurance of Welded Products.

Any feedback, question or request for official interpretation related to any aspect of this document should be directed to IIW via your national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.
Non-destructive testing — Ultrasonic testing — General use of full matrix capture / total focusing technique (FMC/TFM)

1 Scope

This document gives guidance for applying ultrasonic testing with arrays using FMC/TFM techniques. It is intended to promote the adoption of good practice either at the manufacturing stage or for in-service testing of existing installations or for repairs.

Some examples of applications considered in this document, deal with characterisation and sizing in damage assessment.

When testing welds ISO 23864 applies.

A key benefit of using FMC/TFM techniques is that the area within the test volume is presented as an image, which is created by synthetic focusing of the received sound field at each pixel. Comparison with the conventional phased array technique is given in Annex A.

Materials considered are low-alloyed carbon steel, but some recommendations are given for other materials (e.g. austenitic ones).

This document does not include acceptance levels for discontinuities.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 5577, Non-destructive testing — Ultrasonic testing — Vocabulary

ISO 9712, Non-destructive testing — Qualification and certification of personnel

ISO 16810, Non-destructive testing — Ultrasonic testing — General principle

ISO 18563-1, Non-destructive testing — Characterization and verification of ultrasonic phased array equipment — Part 1: Instruments

ISO 18563-2, Non-destructive testing — Characterization and verification of ultrasonic phased array equipment — Part 2: Probes Terms and definitions

ISO 23243, Non-destructive testing — Terminology — Terms used in ultrasonic testing with phased arrays.

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 5577, ISO 23243 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp
3.1 full matrix
matrix consisting of $n \times m$ cells corresponding to all combinations of $m$ transmitted signals and $n$ received signals, with each matrix cell containing an A-scan time domain signal

3.2 total focusing method
TFM
synthetic focusing which consists of a reconstruction, inside a ROI, to focus at many points which form a grid, by processing part or all A-scan information of the applicable transmitter-receiver combinations, taking into account the travelled path from transmitter to image point to receiver, typically performed with full matrix capture (FMC) data

3.3 full matrix capture / total focusing method
FMC/TFM
assembly of a data acquisition scheme and imaging scheme, whereby the acquisition scheme involves a full matrix capture, and the imaging scheme involves computation a total focusing method image, and where the data acquisition and imaging scheme may be performed with several similar technologies, as described in appendix B

3.4 region of interest
ROI
two or three dimensional display, displaying the spatial region of the object for which the image is computed

3.5 FMC/TFM setup
probe arrangement defined by probe characteristics (e.g. frequency, probe element size, wave mode), probe position, and the number of probes

3.6 imaging path
path which ultrasound waves may travel which is taken into account by the imaging algorithm and is defined by:

- a path from a transmitter to an image pixel, optionally including reflections (direct path, indirect path);
- a path from an image pixel to a receiver, optionally including reflections;
- wave type\(^{(1)}\) for each part (leg) of the paths.

Note 1 to entry: A wave mode conversion may occur.

Note 2 to entry: Description of the imaging paths is given in Table 1.

3.7 probe position
distance between the front of the wedge and a reference point

3.8 FMC/TFM indication
pattern or disturbance in the image which may need further evaluation
3.9 scan increment
distance between successive data collection points in the direction of scanning (mechanically or electronically)

3.10 test block
defined and controlled piece of material which allows tests for accuracy and/or performance of an ultrasonic system

3.11 half-matrix capture
HMC
specific data-acquisition process using ultrasonic array probes where all elements in an array are successively used as transmitter, while only elements not used for transmission in previous transmission, or only elements used in previous transmission including the current one, are used as receivers for each transmitted pulse, in order to make use of the reciprocity of signals to limit the amount of collected data

Note 1 to entry: Half-matrix capture results in \( \frac{N(N+1)}{2} \) A-scan signals.

3.12 adaptive focusing
focusing based on calculation of delays on the signals from reference shot(s)

Note 1 to entry: This definition applies to both phased array technology (electronic beam forming, summed A-scan presentation) and to processing technology, e.g. adaptive TFM (ATFM).

Note 2 to entry: A typical example of the use of adaptive focusing is identification of the geometry of refracting, reflecting, or both interface(s) that allow the processing through such interface(s).

3.13 grid
collection of points in ROI for which the image is calculated and stored, defined by the position and relative distance between the points in a specified direction

Note 1 to entry: The grid may extend beyond the test volume. It is not necessarily rectangular and not necessarily uniform. The grid can be two or three dimensional.

Note 2 to entry: This is not necessarily the format that is used to display the results on a display, which is typically rectangular and defined by the screen resolution.

4 Principle of the technique

4.1 General
Both FMC/TFM and PAUT use an array probe where each element of the array is independent of the others. Physical characteristics related to the propagation of waves from the elements of the array, govern the capabilities of both techniques in a similar way. In standard PAUT as in ISO 13588, the active aperture is used to generate sound beams for testing.

In comparison, the FMC/TFM approach typically uses the entire array in order to achieve the best possible focused imaging performance, as for effective focusing the test volume should be within the near-field region of the array. In PAUT, the beams can also be ‘focused’ in a similar way to FMC/TFM by using large apertures or the entire array to create beams that concentrate the sound pressure to specific points, by ensuring that these focal points are within the near-field region of the aperture.
Various imaging paths as described in Table 1 may be used.

Table 1 - Description of the imaging paths

<table>
<thead>
<tr>
<th>Imaging path</th>
<th>Examples</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Diagram]</td>
<td>T-T</td>
<td>transmitter path direct, receiver path direct</td>
</tr>
<tr>
<td></td>
<td>L-L</td>
<td></td>
</tr>
<tr>
<td>or [Diagram]</td>
<td>T-TT, TT-T</td>
<td>transmitter path direct, receiver path indirect</td>
</tr>
<tr>
<td></td>
<td>LL-L, L-LL</td>
<td>or</td>
</tr>
<tr>
<td></td>
<td>LT-T, T-TL</td>
<td>transmitter path indirect, receiver path direct</td>
</tr>
<tr>
<td></td>
<td>TT-L, L-TT</td>
<td></td>
</tr>
<tr>
<td>[Diagram]</td>
<td>TT-TT</td>
<td>transmitter path indirect, receiver path indirect</td>
</tr>
<tr>
<td></td>
<td>LL-LL</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TL-LT</td>
<td></td>
</tr>
<tr>
<td>[Diagram]</td>
<td>TT-TT</td>
<td>transmitter path indirect, receiver path indirect</td>
</tr>
<tr>
<td></td>
<td>LL-LL</td>
<td>(using separate arrays with a known distance)</td>
</tr>
<tr>
<td></td>
<td>TL-LT</td>
<td></td>
</tr>
</tbody>
</table>

NOTE 1 All figures are schematic, not to scale. Due to the principle of reciprocity, transmitter and receiver can be swapped, meaning that the whole path can be followed in the opposite direction; the direction of the arrows for the paths shown in this table is arbitrary. Drawings are intended to illustrate the assumptions made on the imaging path for calculation of the image and do not intend to imply beam forming or focusing of ultrasonic waves.

NOTE 2 The use of indirect imaging paths, especially those aiming at producing an image representative of the reflectors shape, require an accurate assessment of the actual component physical properties, such as ultrasonic wave velocity, wall thickness or non-flat surfaces. This can be compensated for in post-processing, or by using an adaptive imaging algorithm.

4.2 Comparison between FMC/TFM and PAUT

PAUT applies different time delays to the elements of the active aperture in order to control the sound beam within the test object. This results in a beam as governed by the constructive and destructive interference of the wavelets from each element of the active aperture. During the reception phase the
elementary signals are summed to give a single A-scan. In addition to being able to ‘steer’ the beam through a range of angles, in PAUT each beam can also be controlled to focus the sound pressure within the near-field region of the active aperture.

In comparison, FMC/TFM is a post-processing or imaging technique which does not create beams within the test object during the transmission phase. Instead, the sound field transmitted into the component emanates from one element of the aperture and the echoes generated within the component due to this sound field are then recorded on all elements of the aperture, as illustrated in Figure 1. Successive firing of individual elements on the aperture and recording of resultant echoes on all elements is termed full matrix capture (FMC).

Figure 1 — Points in time describing the FMC data collection process

Figure 1 illustrates the various steps of the FMC process:

a) the firing of the first element and a wave front travelling into the test object;

b) the wave front just prior to arrival at a discontinuity in the test object;

c) the reflected echo(es) from the discontinuity returning back in the direction of the array;

d) the wave front just prior to arrival at the elements of the array;

e) the signals being collected on all the elements of the array;

f) the process continues by firing element 2 and is repeated until the last element N of the aperture is fired.

The FMC data can then be processed by algorithms which operate on the data matrix to create images of the reflectors in the component. Total focusing method (TFM) is a term used to describe one such
algorithm which applies calculated delay laws to the FMC data in order to focus the sound on many points (pixels) within a defined region of interest (ROI). This imaging phase (where TFM is applied on the FMC data) is computationally intensive but modern systems are able to achieve real time imaging performance.

5 Requirements for surface condition and couplant

Care shall be taken that the surface condition meets at least the requirements given in ISO 16810. Since typically only individual elements are used as transmitter and since any diffracted signal may also be weak, the degradation of signal quality due to poor surface condition will have a severe impact on testing reliability.

Different coupling media can be used, but their type shall be compatible with the materials to be examined. Examples are: water (possibly containing an agent e.g. wetting, anti-freeze, corrosion inhibitor), contact paste, oil, grease, cellulose paste containing water, etc.

The characteristics of the coupling medium shall remain constant throughout the examination. It shall be suitable for the temperature range in which it will be used.

6 Information required prior to testing

Before any testing can begin, the operator shall have access to all the information as specified:

a) purpose and extent of testing;

b) reporting criteria;

c) manufacturing or operation stage at which the testing is to be carried out;

d) type(s) of parent material and product form (i.e. cast, forged, rolled);

e) geometrical characteristics (especially when reflection is used);

f) requirements for access and surface conditions and temperature;

g) time of testing relative to any heat treatment (if any);

h) acceptance criteria and sizing methodologies shall be defined by specification and provided before testing (to be adapted when recommendations for the applications case will be written).

In case of suspicion of anisotropy, special care shall be taken.

7 Requirements for test personnel

It is recommended that personnel performing testing in accordance with this document shall be qualified to an appropriate UT level in accordance with ISO 9712 or equivalent in the relevant industrial sector.

In addition to a general knowledge of ultrasonic testing, the operators shall be familiar with and have practical experience in the use of FMC/TFM technique. Specific training and examination of personnel should be performed on representative pieces.

These training and examination results should be documented. If this is not the case, specific training and examination should be performed with the finalized ultrasonic testing procedures and selected ultrasonic
testing equipment on representative samples containing natural or artificial reflectors similar to those expected. These training and examination results should be documented.

8 Requirements for test equipment

8.1 General

The full matrix capture (FMC) acquisition process requires a system able to fire the elements one by one and collect the individual element signals from the array probe. Other processes may be used including adaptive processes (see Annex B).

The TFM process may require a fast processing capability and a large memory capacity to handle the large amount of data from the FMC acquisition. Alternative processes may be applied using smaller memory capacity (e.g. based on plane wave imaging, PWI).

8.2 Ultrasonic equipment and display

FMC/TFM equipment may display images of the same type as conventional PA equipment (B-Scan, C-Scan, D-Scan) but may also provide other type of images (see Annex D).

The ultrasonic instrument used for the FMC/TFM testing shall be in accordance with the requirements of ISO 18563-1, if applicable.

The equipment shall be able to acquire a full or partial matrix and either process it by itself or to transmit it to a computer for post-processing. It is recommended that the bandwidth of the ultrasonic system is sufficient to receive signals of at least two times the centre frequency of the probe, and that high- and low-pass filters are set to appropriate values, e.g. high-pass set not higher than half the centre frequency and low-pass set to at least twice the centre frequency. The specific values selected for these parameters, if applicable, shall be explicitly specified within the written procedure.

The data visualised after a TFM process is generally a Region of Interest (ROI) which is a grid of pixels where each pixel represents the computed amplitude (see Annex B). Grids are usually regular, e.g. rectangular, but could be arbitrary (even 3D voxel grids). Regular grids are usually preferred (e.g. to allow optimization in order to enhance the number of images per second).

The grid spacing shall be selected small enough to be able to detect the relevant discontinuities. The minimum spatial resolution of data points within the image (i.e. pixel spacing, nodes) shall be chosen such that the amplitude of a reference reflector is stable within a specified tolerance on small deviations in the probe position. Annex C contains guidance on validation of the amplitude stability.

8.3 Probes

Any linear or matrix array probe can be used for FMC acquisition, but this document is limited to the use of linear phased array probe. Ultrasonic arrays used for the FMC/TFM testing shall be in accordance with the requirements of ISO 18563-2.

The TFM process requires information on the element positions relative to the test object, including details of the delay line or wedge, in order to compute the time of flights associated to the imaging path(s).

Probes in direct contact to the test object can be used but also delay lines, angled wedges or immersion depending on the application. Required details of the delay line or wedge include the shape, dimensions, angle and sound velocity.
In order to achieve good quality images the following properties of the array probe should be taken into consideration:

a) adequately small pitch to avoid spatial aliasing;

b) highly damped elements to decrease the length of the ultrasonic wave train;

c) sufficiently small elements to avoid too much directivity;

d) appropriate aperture and elevation to allow for imaging at a distance away from the probe, as the TFM algorithm has optimal results in the near-field of the probe;

e) wedge dimension optimised for effectiveness;

Typically these requirements are fulfilled by a probe with relative bandwidth $> 60\%$ and an element pitch that is smaller than half the wavelength of the ultrasonic pulse.

The number of dead elements on the active aperture should be less or equal to 1 out of 16 and the dead elements are not adjacent. If this criterion is not met the probe may be used provided appropriate technical justification is given.

### 8.4 Scanning mechanisms

To achieve consistency of the images (collected data), guiding mechanisms may be used and scan encoder(s) shall be used.

The scan increment setting in the primary scanning direction is dependent upon the thickness to be examined. Recommended values are given in Table 2.

Other values may be used provided appropriate technical justification is provided.

The scan increment setting perpendicular to the primary scanning direction when applicable shall be chosen in order to ensure the coverage of the testing volume.

An additional function of scanning mechanisms is to provide position information in order to enable the generation of position-related FMC/TFM images.

<table>
<thead>
<tr>
<th>Thickness $t$ [mm]</th>
<th>Scan increment $S$ [mm]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t \leq 6$</td>
<td>0,5</td>
<td>-</td>
</tr>
<tr>
<td>$6 &lt; t \leq 10$</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>$10 &lt; t \leq 150$</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>$t &gt; 150$</td>
<td>3</td>
<td>Scanning speed shall be carefully adapted to the equipment capabilities</td>
</tr>
</tbody>
</table>

Scanning mechanisms in FMC/TFM can either be motorised or manually driven. They shall be guided by means of a suitable guiding mechanism. The tolerance for the probe position depends on the application and shall be given in the written test procedure.

The scanning speed shall be suitable for the equipment used in order to avoid loss of data.