INTERNATIONAL STANDARD

ISO 23865

First edition
2021-01

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

Essais non destructifs — Contrôle par ultrasons — Utilisation générale de l'acquisition de la matrice intégrale/technique de focalisation en tous points (FMC/FTP) et de techniques associées

Reference number
ISO 23865:2021(E)

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Foreword

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

Any feedback or questions on this document should be directed to the user's 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) and related technologies

IMPORTANT — The electronic file of this document contains colours which are considered to be useful for the correct understanding of the document. Users should therefore consider printing this document using a colour printer.

1 Scope

This document gives general provisions for applying ultrasonic testing with arrays using FMC/TFM techniques and related technologies. 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 characterization and sizing in damage assessment.

Materials considered are low-alloyed carbon steels and common aerospace grade aluminium and titanium alloys, provided they are homogeneous and isotropic, but some recommendations are given for other materials (e.g. austenitic ones).

This document does not include acceptance levels for discontinuities.

For the application of FMC/TFM to testing of welds, see ISO 23864.

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 NDT personnel*

ISO 16810, *Non-destructive testing — Ultrasonic testing — General principles*

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*

ISO 23243, *Non-destructive testing — Ultrasonic testing with arrays - Vocabulary.*

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

— IEC Electropedia: available at http://www.electropedia.org/

3.1
full matrix capture/total focusing technique
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 a total focusing technique, and where the data acquisition and imaging scheme may be performed with several similar technologies.

Note 1 to entry: TFM is often indicated as "total focusing method" but, in this document, the term "method" in NDT is reserved for applying a physical principle (see ISO 9712).

3.2
FMC/TFM setup
probe arrangement defined by probe characteristics (e.g. frequency, probe element size, wave mode), probe position, and the number of probes.

Note 1 to entry: Unless stated otherwise, in this document “TFM” and “FMC” refer to the techniques as defined in ISO 23243, and to all related technologies see for example Annex B and ISO 23243.

4 Principle of the technique

4.1 General

Both FMC/TFM and phased array ultrasonic testing (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 because for effective focusing the test volume should be within the near-field region of the array, which is maximized by using the entire array. In the PAUT technique, 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

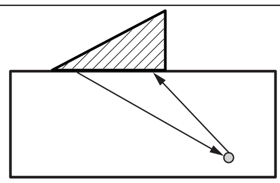
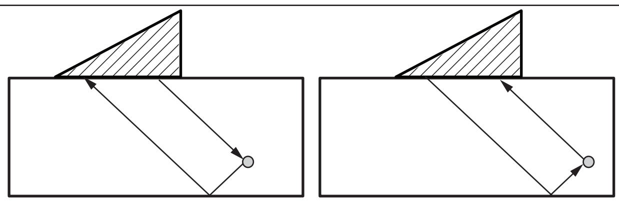
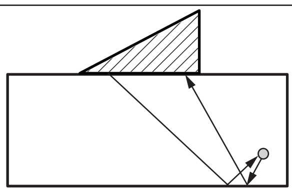
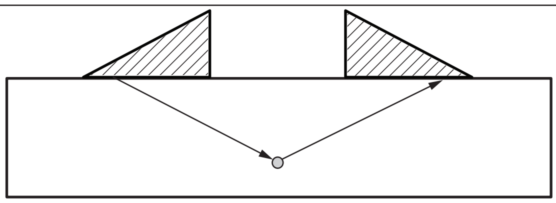
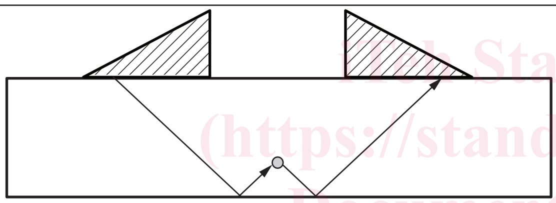
Imaging path	Examples	Description
	T-T L-L	transmitter path direct, receiver path direct
NOTE 1 All figures are schematic, not to scale. Due to the principle of reciprocity, transmitter and receiver can be swapped, meaning that the whole path can be followed in the opposite direction. The direction of 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. NOTE 3 L corresponds to longitudinal wave mode and T to transversal wave mode.		

Table 1 *(continued)*

Imaging path	Examples	Description
 OR	T-TT, TT-T LL-L, L-LL LT-T, T-TL TT-L, L-TT	transmitter path direct, receiver path indirect or transmitter path indirect, receiver path direct
	TT-TT LL-LL TL-LT	transmitter path indirect, receiver path indirect
	L-L T-T	transmitter path direct, receiver path direct (using separate arrays with a known distance)
	TT-TT LL-LL TL-LT	transmitter path indirect, receiver path indirect (using separate arrays with a known distance)

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.

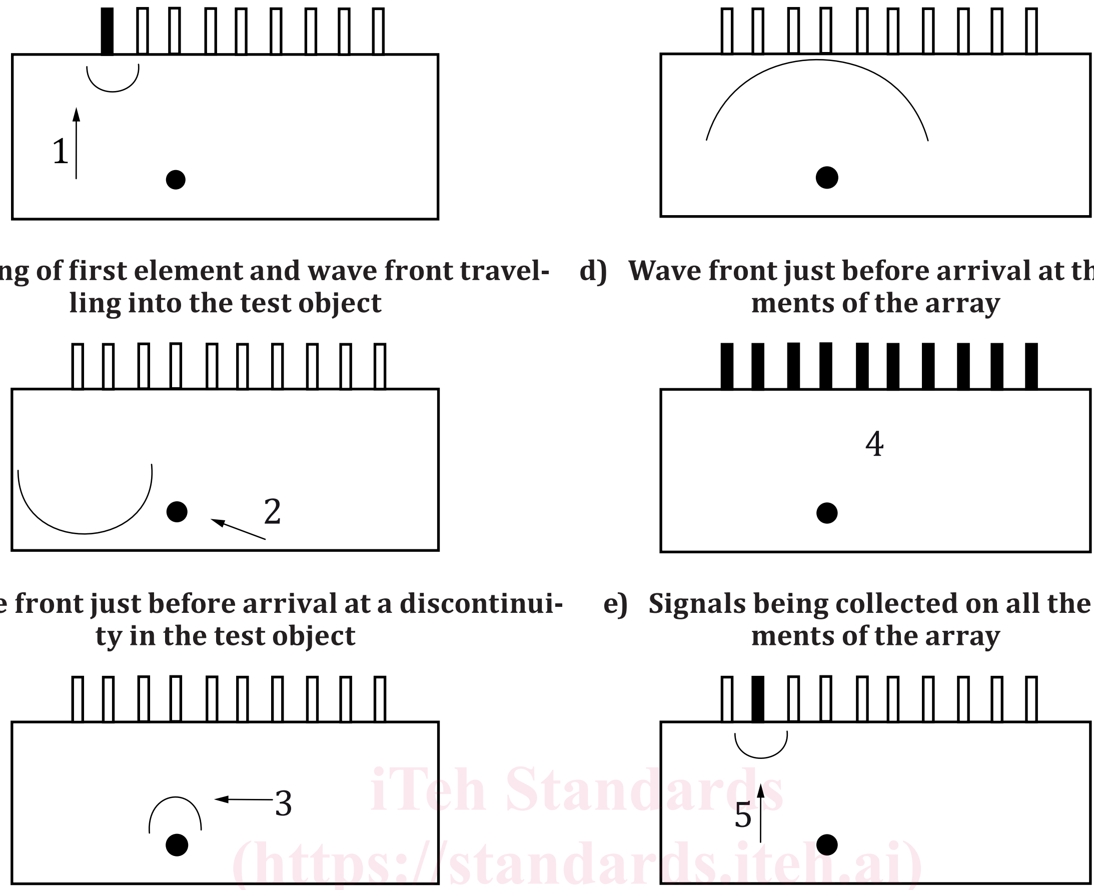
NOTE 2 The use of indirect imaging paths, especially those aiming at producing an image representative of the reflectors shape, require an accurate assessment of the actual component physical properties, such as ultrasonic wave velocity, wall thickness or non-flat surfaces. This can be compensated for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

NOTE 3 L corresponds to longitudinal wave mode and T to transversal wave mode.

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, TFM is a post-processing or imaging technique applied to FMC signals that 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 array and the echoes generated within the component due to this sound field are then recorded on all elements of the array, as illustrated in Figure 1. Successive firing of individual elements on the array and recording of resultant echoes on all elements is termed full matrix capture (FMC).



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

d) Wave front just before arrival at the elements of the array

b) Wave front just before arrival at a discontinuity in the test object

e) Signals being collected on all the elements of the array

c) Reflected or diffracted echo(es) from the discontinuity returning back in the direction of the array

f) Process continued by firing element 2 and repeated until the last element N of the array is fired

Key

1 wave front transmitted by element 1

2 discontinuity

3 wave front reflected or diffracted by the discontinuity

4 receiving elements

5 wave front transmitted by element 2

Figure 1 — Typical example of points in time describing the FMC data collection process

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

A more detailed comparison is given in Annex A.

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 any diffracted signal can also be weak, the degradation of signal quality due to poor surface condition has 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

6.1 General

ISO 18563-3 gives useful information.

6.2 Items to define prior to procedure development

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

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 application cases are written).

In case of any suspicion of anisotropy in the material to be tested, special care shall be taken.

7 Requirements for test personnel

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 product or industrial sector.

In addition to general knowledge of ultrasonic testing, the operators shall be familiar with and have practical experience in the use of FMC/TFM technique or related technology.

Specific training and examination shall 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 shall be documented.

8 Requirements for test equipment

8.1 General

The 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 can 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 Instrument

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

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

The ultrasonic instrument shall be able to acquire a full or partial matrix and either process it by itself or transmit it to a computer for post-processing. It is recommended that the length of the acquired A-scan is sufficient, considering the imaging path that will be processed or post-processed. 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 visualized after a TFM process is generally a region of interest (ROI) which is a grid where each grid point represents the computed amplitude (see 4.2 and Annex B). Grids are usually regular, e.g. rectangular, but can be arbitrary (even 3D). 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. grid point spacing) 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 times of flight 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 can be used depending on the application. Required details of the delay line or wedge include the type, 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 optimized 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 as determined in the wedge (or in the part under testing when no wedge is used).

The number of dead elements on the active aperture should be less than or equal to 1 out of 16 and any dead elements are not allowed to be adjacent to each other. 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 on 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 settings perpendicular to the primary scanning direction, when applicable, shall be chosen in order to ensure the coverage of the test 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 2 — Scan increment values in the primary scanning direction in accordance with thickness

Dimensions in millimetres

Thickness t	Scan increment
$t \leq 6$	0,5
$6 < t \leq 10$	1
$10 < t \leq 150$	2
$t > 150$	3

Scanning mechanisms in FMC/TFM can either be motorized or manually driven. They shall be guided by means of a suitable guiding mechanism. The tolerances for the probe position depend on the application and it 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.

8.5 Sampling frequency

The sampling frequency of the A-scans should be at least five times the nominal centre frequency of the probe. If interpolation (up-sampling) of the A-scans is used, the hardware sampling frequency may be as low as three times the upper cut-off frequency (-6 dB) of the probe.

The theoretical limit according to the Nyquist sampling theorem is twice the upper frequency of the signal, but additional margin should be provided for non-ideal filters before analogue-to-digital conversion.

8.6 Data processing

The processing of A-scan data based on time of flight (from the transmitter to an image point and back to the receiver) is generally referred to as imaging. This is the basis of TFM. Optionally, the processing algorithms can also take into account physical parameters to improve the quality of the resulting image, like directivity, divergence, attenuation, reflectivity, transmission coefficients and apodization.

A detailed description of TFM is given in 4.2 and Annex B. Descriptions of related technologies are given in ISO 23243 and Annex B, such as sampling phased array (SPA), plane wave imaging (PWI) and inverse wave field extrapolation (IWEX).

Once the data has been processed into an image, additional image processing may be applied afterwards for further optimization/visualization.

8.7 Evaluation of TFM indications

The recommended sizing methods are:

a) extraction of signals scattered (diffracted) from different points on the discontinuity and deducing the extent of the discontinuity based on images of the diffracted signals;

b) using amplitude drop with respect to the maximum TFM indication response to establish the extent of the discontinuity.

In accordance with the application requirements, other sizing methods may be used.

9 Benefits of various imaging paths

By including boundary reflections in the path from transmitter to receiver, discontinuities in the ROI can be imaged from different directions using both reflection and diffraction signals, which can improve the performance and reliability of testing.

Volumetric discontinuities resulting in reflection (in many directions) and edges of discontinuities resulting in diffraction (in many directions) are typically detected with each imaging path that covers the region of the discontinuity.

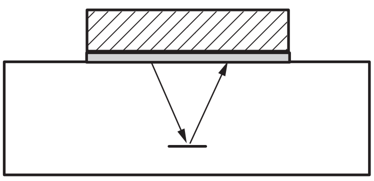
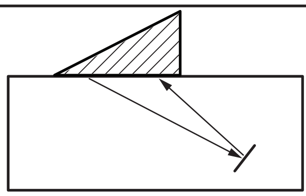
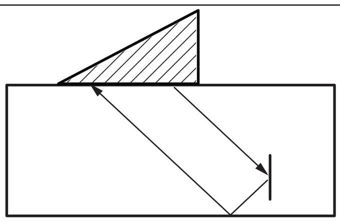
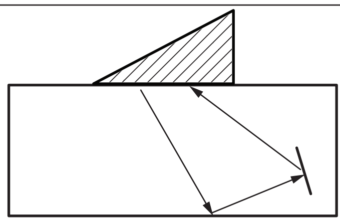
In general, discontinuities with an orientation (planar discontinuities) are best detected with imaging paths (see Table 3) where the incident angle and reflected angle on the discontinuity are:

a) (about) perpendicular to the discontinuity orientation;

b) (about) symmetric to the normal direction of the discontinuity; or

c) according to Snell's law if mode conversion occurs at the discontinuity.

Table 3 — Advantages of different imaging paths

Imaging path	Orientation of discontinuities for reflection
 	Discontinuities with (near) horizontal orientation. Discontinuities with other orientations depending on incident and reflected angles.
 	Discontinuities with (near) vertical orientation. Discontinuities with other orientations if mode conversion occurs in the path.

