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Non-destructive testing — Radiation methods for computed tomography —

Part 2:
Principles, equipment and samples

Essais non destructifs — Méthodes par rayonnements pour la tomographie informatisée —

Partie 2: Principes, équipements et échantillons

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Foreword

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This third edition cancels and replaces the second edition (ISO 15708-2:2017), which has been technically revised.

The main changes are as follows:

— addition of normative references;

— correction of the vacuum level for activating the turbo pump in A.1.1;

— addition of photon counting as an example under semiconductors in A.2.3;

— editorial changes.

A list of all parts in the ISO 15708 series can be found on the ISO website.

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Non-destructive testing — Radiation methods for computed tomography —

Part 2:
Principles, equipment and samples

1 Scope

This document specifies the general principles of X-ray computed tomography (CT), the equipment used and basic considerations of sample, materials and geometry.

This document is applicable only to industrial imaging (i.e. non-medical applications) and provides a consistent set of definitions of CT performance parameters, including the relationship between these performance parameters and CT system specifications.

This document is applicable to industrial computed tomography.

This document does not apply to other techniques of tomography, such as translational tomography and tomosynthesis.

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 15708-1, *Non-destructive testing — Radiation methods for computed tomography — Part 1: Terminology*

ISO 15708-3, *Non-destructive testing — Radiation methods for computed tomography — Part 3: Operation and interpretation*

ISO 15708-4, *Non-destructive testing — Radiation methods for computed tomography — Part 4: Qualification*

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

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 15708-1 apply.

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

— ISO Online browsing platform: available at https://www.iso.org/obp

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

4 General principles

4.1 Basic principles

Computed tomography (CT) is a radiographic inspection method which delivers three-dimensional information on an object from a number of radiographic projections either over cross-sectional planes (CT slices) or over the complete volume. Radiographic imaging is possible because different materials have different X-ray attenuation coefficients. In CT images, the linear X-ray attenuation coefficients are displayed as different CT grey values (or in false colour). For conventional radiography, the three-dimensional object is X-rayed from one direction and an X-ray projection is produced with the corresponding information aggregated over the ray path. In contrast, multiple X-ray-projections of an object are acquired at different projection angles during a CT scan. From these projection images, the actual slices or volumes are reconstructed. The fundamental advantage compared to radiography is the preservation of full volumetric information. The resulting CT image (2D-CT slice or 3D-CT volume), is a quantitative representation of the X-ray linear attenuation coefficient averaged over the finite volume of the corresponding volume element (voxel) at each position in the sample.

The linear attenuation coefficient characterizes the local instantaneous rate at which X-rays are attenuated as they propagate through the object during the scan. The attenuation of the X-rays as they interact with matter is the result of several different interaction mechanisms: Compton scattering and photoelectric absorption being the predominant ones for X-ray CT. The linear attenuation coefficient depends on the atomic numbers of the corresponding materials and is proportional to the material density. It also depends on the energy of the X-ray beam.

4.2 Advantages of CT

Among the radiographic techniques, CT can be an excellent examination technique whenever the primary goal is to locate and quantify volumetric details in three dimensions. In addition, since CT is X-ray based, it can be used on metallic and non-metallic samples, solid and fibrous materials and smooth and irregularly surfaced objects.

In contrast to conventional radiography, in which the internal features of a sample are projected onto a single image plane and thus are superposed on each other, in CT images the individual features of the sample appear separated from each other, preserving the full spatial information.

With proper calibration, dimensional inspections and material density determinations can also be carried out.

Complete three-dimensional representations of examined objects can be obtained either by reconstructing and assembling successive CT slices (2D-CT) or by direct 3D CT image (3D-CT) reconstruction. Computed tomography is therefore valuable in the industrial application areas of non-destructive testing, 2D and 3D metrology and reverse engineering.

CT has several advantages over conventional metrology methods:

— acquisition without contact;

— access to internal and external dimensional information;

— a direct input to 3D modelling especially of internal structures.

In some cases, dual energy (DE) CT acquisitions can help to obtain information on the material density and the average atomic number of certain materials. For known materials, the additional information can be used for improved discrimination or improved characterization.

4.3 Limitations of CT

CT is an indirect test procedure and absolute CT measurements (e.g. of the size of material inhomogeneities or of wall thicknesses) shall be based on a comparison with other absolute measurement procedures in accordance with ISO 15708-3. Another potential drawback of CT imaging is the possible occurrence of artefacts (see 4.5) in the data. Artefacts limit the ability to quantitatively extract information from an image. Therefore, as with any examination technique, the user shall be able to recognize and discount common artefacts subjectively.

Like any imaging system, a CT system can never reproduce an exact image of the scanned object. The accuracy of the CT image is dictated largely by the competing influences of the imaging system, namely spatial resolution, statistical noise and artefacts. Each of these aspects is discussed in 4.4.1. See ISO 15708-3 for a more detailed description.

CT grey values cannot be used to identify unknown materials unambiguously unless a priori information is available, since a given experimental value measured at a given position can correspond to a broad range of materials.

Furthermore, there shall be sufficient X-ray transmission (≥ 10 %, see 8.2) through the sample at all projection angles without saturating any part of the detector.

4.4 Main CT process steps

4.4.1 Acquisition

Multiple projections are systematically recorded during a CT scan: the images are acquired from a number of different viewing angles. Feature recognition depends, among other factors, on the number of angles from which the individual projections are acquired. The CT image quality can be improved by increasing the number of projections in a scan.

As all image capture systems contain inherent artefacts, CT scans usually begin with the capture of offset and gain reference images to allow flat field correction; using black (X-rays off) and white (X-rays on with the sample out of the field of view) images to correct for detector anomalies. The capture of reference images for distortion correction (pin cushion distortion in the case of camera-based detector systems with optical distortion), and centre of rotation correction can also take place at this stage. These corrections are applied to each subsequently acquired image of the CT data set. Some systems can be configured to enhance either the X-ray settings or the image to ensure that the background intensity level of the captured images remains constant throughout the duration of the CT scan.

The quality of a CT image depends on a number of system-level performance factors, with one of the most important being spatial resolution.

Spatial resolution is generally quantified in terms of the smallest separation at which two features can be distinguished as separate entities. The limits of spatial resolution are determined by the design and construction of the system and by the resolution and number of CT projections. The resolution of the CT projection is limited by the maximum magnification that can be used while still imaging all parts of the sample at all rotation angles.

It is important to note that the smallest feature that can be detected in a CT image is not the same as the smallest that can be resolved spatially. A feature considerably smaller than a single voxel can affect the voxel to which it corresponds to such an extent that it appears with a visible contrast so that it can be easily detected with respect to adjacent voxels. This phenomenon is due to the “partial-volume effect”.

Although region-of-interest CT (local tomography) can improve spatial resolution in certain regions of larger objects, it introduces artefacts (due to incomplete data) which can sometimes be reduced by special processing.

Radiographic imaging, as used for CT examination, is always affected by noise. In radiography this noise arises from two sources:

a) intrinsic variation corresponding to photon statistics in the emission and detection of photons;

b) variations specific to instruments and processing used.

Noise in CT projections is often amplified by the reconstruction algorithm. In CT images, statistical noise appears as random variation superimposed on the CT grey value of each voxel, limiting the density resolution.

Although statistical noise is unavoidable, the signal-to-noise ratio can be improved by increasing the number of projections and/or time of exposure for each of them, the intensity of the X-ray source or the voxel size. However, some of these measures will decrease spatial resolution. This trade-off between spatial resolution and statistical noise is inherent in computed tomography.

4.4.2 Reconstruction

A CT scan initially produces a number of projections of an object. The subsequent reconstruction of the CT image from these individual projections is the main step in computed tomography, which distinguishes this examination technique from other radiographic techniques.

The reconstruction software can apply additional corrections to the CT projections during reconstruction, e.g. reduction of noise, correction of beam hardening and/or scattered radiation.

Depending on the CT system, either individual CT slices or 3D CT images are reconstructed.

4.4.3 Visualization and analysis

This step includes all operations and data manipulations, for extracting the desired information from the reconstructed CT image.

Visualisation can either be performed in 2D (slice views) or in 3D (volume). 2D visualisation allows the user to examine the data slice-wise along a specified axis (generally it can be an arbitrary path).

For 3D imaging, the CT volume or selected surfaces derived from it, are used for generating the desired image according to the optical model underlying the algorithm. The main advantage of this type of visualisation is that the visual perception of the image corresponds well with the natural appearance of the object for the human eye, although features can appear superimposed in the 2D-representation on a screen.

During visualisation, additional artefacts of different origin can occur, especially in the 3D imaging of the CT volume. Such artefacts due to sampling, filtering, classification and blending within the visualisation software depend on the hardware and software used, as well as the visualisation task at hand. Therefore, such artefacts are not included in the definition of artefacts as found in 4.5. Nevertheless, the user should be aware that data can be misinterpreted in this process step.

To highlight features of interest during visualisation, different digital filter operations can be performed. It is characteristic of all these operations that although they enhance one or more properties of the data, they simultaneously deteriorate other properties (for example: highlighting the edges deteriorates recognition of inner structures of an object). Therefore, digital filters should always be used cautiously for specific tasks, being aware, which benefits and which detriments, they are associated with.

A computer used for 3D visualisation should be able to process the complete volume of interest in its main memory. The corresponding monitor should have a resolution, a dynamic range and settings sufficient for the given visualisation task. Adequate vision of the personnel shall be ensured in accordance with ISO 9712.

4.5 Artefacts in CT images

An artefact is an artificial feature which appears on the CT image but does not correspond to a physical feature of the sample. Artefacts result from different origins; they can be classified into artefacts arising from the measurement itself and the equipment (artefacts due to a finite beam width, scattered radiation, instabilities and detector peculiarities), and artefacts inherent to the technique (e.g. beam hardening). Artefacts can also be divided into acquisition artefacts (e.g. scattered radiation, ring artefacts) and reconstruction artefacts (e.g. cone beam artefacts). Some artefacts can be eliminated by using an appropriate measurement technique with suitable parameters, while others can only be reduced in their extent. Artefacts can be detrimental for specific measurement or analysis tasks, but can also have no impact on certain other analyses. With this fact in mind, the type and extent of artefacts in a data set has to be evaluated in the context of the corresponding analysis task.

Noise and the partial volume effect are not considered as artefacts in this document.

More details are given in ISO 15708-3:2017, 5.5.

5 Equipment and apparatus

5.1 General

In relation to performance, a CT system can be considered as comprising four main components: the X-ray source, detector, sample manipulation stages (including any mechanical structures that influence image stability) and reconstruction/visualisation system.

Generally, the source and detector will be fixed while the sample rotates in the beam to acquire the necessary set of projections. For example, in scanners designed for *in vivo* animal studies or for imaging large structures, the source and detector can orbit around the sample.

In most micro-/nano- or sub-micro-tomography systems, the resolution is determined primarily by the X-ray focal spot size. Due to geometric magnification, the detector element spacing can be much larger than the computed voxel size, and a thicker and therefore more efficient scintillator can be used. A disadvantage of this approach is that the sample should be located very close to the source in order to achieve high magnification ratios. This is particularly problematic if the sample is to be mounted in some form of environmental chamber or, for example, an in-situ loading stage. This imposes a lower limit on the source to sample distance, thus reducing X-ray fluence (resulting in a lower signal-to-noise ratio and/or increased acquisition time) and requiring the detector to be mounted proportionately further away in order to achieve the same magnification factor. Alternatively, if the sample to detector distance is low compared with the source to sample distance, the detector resolution becomes the limiting factor, rather than the spot size. In this case, the increased source to detector distance again means reduced X-ray fluence and high-resolution detectors tend to require thinner and hence less efficient scintillators.

CT systems can be optimised for resolution, energy, speed of acquisition or simply cost. Although a particular system can operate in a wide range of conditions, it will operate optimally in a much smaller range and the user should consider the main application when choosing one model over another and not simply over-specify.

For example, a high-resolution CT system (small X-ray focal spot size) can have a considerably lower flux output at more modest resolution settings than one designed to operate at modest resolution only. Furthermore, a high-performance rotation stage for a high-resolution scanner will have a much smaller load limit. Similarly, a system designed for high-energy imaging will require a thicker phosphor screen, giving poorer resolution compared with a thinner screen, which is adequate at lower energies.

Some CT systems can provide interchangeable X-ray target heads (transmission or reflection, see Annex A) and/or interchangeable detectors.

When comparing resolution and scan times on different CT systems, it is important to consider the signal-to-noise ratio (SNR), see ISO 15708-3:2017, 5.1.3. The resolution and scan times depend on the X-ray exposure, i.e. the faster the scan, the worse the SNR, as well as on the sample type and geometry. A sample with a high void volume fraction (or with a high proportion of relatively low absorbing regions), such as a foam or cancellous bone sample, will exhibit a better SNR than a more homogeneous sample.

For a given exposure, the best SNR is obtained when the X-ray accelerating voltage is set so that approximately 10 % to 20 % transmission through the sample is achieved. If the transmission is too low, the low number of detected photons leads to excessive noise. Conversely, if the transmission is too high, the contrast) is too low. However, the SNR does not vary sharply with voltage, and simulations of X-ray attenuation in aluminium indicate that the SNR only drops by 20 % of the peak value if the voltage is set to 35 % or 40 % transmission. For a given sample size, the X-ray exposure required to maintain a fixed SNR is proportional to the fourth power of resolution (for a given detector). For example, doubling the resolution requires a 16-fold increase in exposure, while a 10-fold increase in resolution requires a 10,000-fold increase in exposure. Therefore, it is crucial to use the same or similar samples when comparing the image quality of one system to another.

5.2 Radiation sources

Most industrial CT systems use a high-voltage generator driving the X-ray source, which can be subdivided into three main types:

— open tube (or vacuum demountable) x-ray sets;

— sealed tube constant potential x-ray sets;

— linear accelerators.

Each source type has a speciality; sometimes systems are supplied with more than one source so they can be used over a broader range of samples. The selection of a suitable X-ray source depends on the range of samples (size, composition and material density) to be inspected and the resolution at which they are to be inspected.

X-ray set manufacturers will often quote a single focal spot size, this is a “nominal” measurement at a specific energy setting. The size of the focal spot varies depending upon the settings for voltage (kV) and current (µA/mA); the higher the power the larger the focal spot will become.

The focal spot size and the feature recognition (which is sometimes referred to by system manufacturers) are not the same as the spatial resolution of the CT system. The feature recognition is the ability of the overall system to display an image of an object, or feature within an object, of a certain size. For example, it is possible for a system with an X-ray set being run at an energy that is producing a focal spot size of around 5 µm to display an image of a dense wire cross-hair made from wire less than 1 µm in diameter. This is rather an indication of the X-ray absorption characteristics of the material that the wire is made from, than the actual resolution of the CT system, see 4.4.1.

The X-ray beam is often filtered to reduce lower energy X-rays and therefore to reduce scattering and beam hardening effects.

Further details are given in Annex A.

5.3 Detectors

A radiation detector is used to measure the transmission of X-rays through the object along the different ray paths. The purpose of the detector is to convert the incident X-ray flux into an electrical signal that can be handled by conventional electronic processing techniques. The number of ray sums in a projection shall be comparable to the number of elements on the side of the image matrix. These considerations mean that modern scanners tend to use large detector arrays that often contain several hundred to over thousands or millions of sensors.

Filtration at the detector using material inserted into the ray path in front of the detector (behind the test object) is helpfully. The filter absorbs (and scatters) radiation depending on its material characteristics, as specified in 5.1. In addition, each detector performs a certain amount of filtration when the rays pass through the detector housing. Additional filtration can be used to reduce the intensity of detected scatter.

Typically, three types of detectors are in use:

a) gas ionization detectors;

b) scintillation detectors;

c) semiconductor detectors.

Further details are given in Annex A.

5.4 Manipulation

Mechanical scanning devices ensure the relative movement between the test object, the source and the detector. In principle, it makes no difference whether the test object is moved systematically relative to the source and detector or whether the source and detector are moved relative to the test object. Physical