SLOVENSKI STANDARD
oSIST prEN 16016-2:2010

01-marec-2010

Neporušitvene preiskave - Sevalna metoda - Računalniška tomografija - 2. del: Osnove, oprema in vzorci

Non destructive testing - Radiation method - Computed tomography - Part 2: Principle, equipment and samples

Zerstörungsfreie Prüfung - Durchstrahlungsverfahren - Computertomographie - Teil 2: Grundlagen, Geräte und Proben

Essais non destructifs - Méthodes par rayonnements - Tomodensitométrie - Partie 2 : Principes, équipements et échantillons

Ta slovenski standard je istoveten z: prEN 16016-2

ICS:

19.100 Neporušitveno preskušanje Non-destructive testing

oSIST prEN 16016-2:2010 **en,fr,de**

EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

DRAFT
prEN 16016-2

November 2009

ICS 19.100

English Version

Non destructive testing - Radiation method - Computed tomography - Part 2: Principle, equipment and samples

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EUROPEAN COMMITTEE FOR STANDARDIZATION
COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

Management Centre: Avenue Marnix 17, B-1000 Brussels

Ref. No. prEN 16016-2:2009: E

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Foreword

This document (prEN 16016-2:2009) has been prepared by Technical Committee CEN/TC 138 “Non-destructive testing”, the secretariat of which is held by AFNOR.

This document is currently submitted to the CEN Enquiry.

The standard consists of the following parts, under the general title Non Destructive Testing – Radiation method – Computed tomography:

— Part 1 : Terminology

— Part 2 : Principle, equipment and samples

— Part 3 : Operation and interpretation

— Part 4 : Qualification

Introduction

This document gives guidelines for the general principles of X-ray computed tomography (CT) applicable to industrial imaging (in the context of this standard, industrial means non-medical applications); it also gives a consistent set of CT performance parameter definitions, including how these performance parameters relate to CT system specifications. This document deals with computed axial tomography and excludes other types of tomography such as translational tomography and tomosynthesis.

1 Scope

This part gives the general principles of computed tomography (CT). It describes the equipment used and basic considerations of sample, materials and geometry.

2 Normative references

The following referenced documents are indispensable for the application 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.

EN 473, *Non destructive testing - Qualification and certification of NDT personnel - General principles*.

prEN 16016-1, *Non Destructive Testing – Radiation method – Computed tomography - Terminology*.

prEN 16016-3, *Non Destructive Testing – Radiation method – Computed tomography - Operation and Interpretation.*

prEN 16016-4, *Non Destructive Testing – Radiation method – Computed tomography - Qualification*.

3 Terms and definitions

For the purposes of this document, the terms and definitions given in prEN 16016-1 apply.

4 General principles

4.1 Basic principles

Computed tomography is a radiographic inspection method which delivers three-dimensional information of 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 X-ray linear attenuation coefficients are represented 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 volume 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

Computed tomography (CT) is a radiographic method that can be an excellent examination technique whenever the primary goal is to locate and quantify volumetric details in three dimensions. Also, since the method 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, where 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 separate from each other, preserving the full spatial information.

With proper calibration, dimensional inspections and density determinations can also be made.

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 thus 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 of the density and the average atomic number of certain materials. In the case of known materials the additional information can be traded for improved conspicuousness or improved characterization.

4.3 Limitations of CT

CT is an indirect test procedure and measurements (e.g. of the size of material faults; of wall thicknessesmust be compared with another absolute measurement procedure, see WI 001380147.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 must 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 briefly in clause 4.4.1. A more complete description will be found in prEN 16016-3.

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 may correspond to a broad range of materials.

Another important consideration is to have sufficient X-ray transmission through the sample at all projection angles (see 8.2) without saturating any part of the detector.

4.4 Main CT process steps

4.4.1 Acquisition

During a CT scan multiple projections are taken in a systematic way: 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 taken. The CT image quality can be improved if the number of projections of a scan is increased.

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. Each subsequent captured image for the CT data set has these corrections applied to it. Some systems can be configured to make minor adjustments to either the X-ray settings or through image enhancement 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 of 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 notice 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 specified regions of larger objects, it introduces artefacts (due to incomplete data) which can sometimes be reduced with special processing.

Radiographic imaging as used for CT examination is always affected by noise. In radiography this noise arises from two sources: (1) intrinsic variation corresponding to photon statistics related to the emission and detection of photons and (2) variations specific to instruments and processing used. Noise in CT projections is often amplified by the reconstruction algorithm. In the CT images statistical noise appears as a random variation superimposed on the CT grey value of each voxel and limits contrast discrimination.

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 methods.

The reconstruction software may 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 Visualisation 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 defined 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 may 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 are dependent 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 clause 4.5. Nevertheless the user should be aware that misinterpretation of the data might also occur in this process step.

To highlight features of interest during visualisation different digital filter operations can be performed. A characteristic of all these operations is 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 the 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 is to be ensured, see EN 473.

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 method (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 may be detrimental for specific measurement or analysis tasks, but may 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 standard.

More details are given in clause 5.5 of prEN 16016-3.

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 (the latter including any mechanical structure that influences image stability) and reconstruction/visualisation system.

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