Numeric Prediction of the Detail Visibility in Industrial X-Ray Computed Tomography by Human Observers

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Abstract: Industrial Computed Tomography (iCT) is applied in industry for flaw detection, flaw evaluation and dimensional measurement. This requires the correct experimental system settings for sufficient visibility and detectability of details and structure elements. This is an essential tool for long term monitoring of the detail sensitivity of CT scanners. The visibility of indications by human observers on a monitor in cross sectional 2D CT-images can be estimated from the square root of the visible flaw area, the Contrast to Noise Ratio (CNR) and the Modulation Transfer Function (MTF). The ASTM guide E 1441 describes a more detailed procedure for the determination of the minimum contrast for the visibility of flaws based on three essential functions for the prediction of the visibility of small circular indications in iCT slice images. This is the Contrast Discrimination Function (CDF), the Modulation Transfer Function (MTF) as described in the latest revision of ASTM E 1695, and the Contrast Detail Diagram (CDD). All these functions analyse the contrast as function of the spatial frequency in digital 2D slice images. The functions do not describe, how to calculate the visibility limit for human observers. The concept for the automated calculation of the visibility limit of circular indications in reconstructed slice images is discussed in this paper. It is finally determined from the intersection point of the MTF with the Contrast Detail Diagram, which is the combination of CDF and MTF, and a physiological factor c. The new measurement procedures for the prediction of the detail visibility by MTF and CDD was tested with test phantoms and be verified by modelling and measurements. A Round Robin test was conducted with more than 10 parties to verify the visibility formula and the procedure for determination of the visibility limit from the combination of these functions. A form factor is considered to compare cylinder holes with pore indications. Conclusions will be reported and recommendations will be given for the determination of the correct physiological factor c.

Keywords: NDT-wide, Radiographic Testing (RT), Computed Tomography, detail visibility
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Overview

- Algorithm for computer-based prediction of the detectability of holes and pores by human operators in CT slice images
  - Concept: Contrast Detail Diagram (ASTM E 1441)
  - Modulation Transfer Function (MTF) for measuring the relative contrast depending on the hole diameter (ASTM E 1695-20)
  - Contrast discrimination function (CDF) based on CNR (ASTM E 1695-20)
- New test specimens for quality assessment and monitoring of CT scanners
  - New single hole test specimens (ASTM project: "Phantom B1")
  - New test specimens with hole groups (ASTM project: Phantom B2)
Visibility of Holes in Image Quality Indicators

What is already known? → Detectability depends on diameter and CNR.

Image quality verification in the USA (ASTM E 1025) is based on hole detectability even with the same CNR.

Hole Plate IQI

5/1000 Inches IQI (127 µm thick) with 1T, 2T, 4T hole

2T and 4T recognizable with the same CNR

ASTM Hole Plate IQIs vs. Wires

Large holes are clearly visible.

Small holes are sometimes not recognizable.

Modelling
New IQI for CT (ASTM Phantom B)

Measurement with hole-disc test specimen

- Monitoring of contrast detail sensitivity.
- *Does the CT system have the desired sensitivity?*

Example: Al-Disk
40 mm diameter
Holes: 50 µm - 250 µm

The measurement can be carried out together with the test phantom or separately.
Background

- Image quality parameters in CT slice images and digital radiographs
  - The image quality (grey images) depends on:
    - Indication contrast, noise, and spatial resolution,
    - Flaw shape and size.

- Measurement of image quality with image quality indicators (IQI)
  - In radiography, it is the equivalent penetratoremeter sensitivity (EPS), standardised for plate-hole IQIs in ASTM (e.g. ASTM E1025) and is also used for wires (ASTM E747, ISO 19232-1).
  - The prediction of EPS is based on the modified Rose concept of 1946 for optical cameras and human observers.
  - The concept of contrast discrimination diagrams (CDD) was developed in the seventies for computed tomography (CT), and is based on the spectral analysis of noise, contrast and modulation transfer function (MTF).
Hole-Phantom Designs

Ewert, Da Silva, Zscherpel
Phantom 1 (KOWOTEST, BAM, Petrobras)

Herold (VisiConsult)

Cartesian Matrix

Star matrix

New ASTM-Standard design
Roth (Baker Hughes, Waygate)

Star design
The smallest visible hole in row 5 has a diameter of 100 μm (measured with microscope and μ-CT).

All five holes must be visible.

We see small ring artifacts and hardening (1 mm Cu in front of the X-ray tube).

Conditions:
- 160 kV, I = 180 μA, Magn. = 3
- SDD = 666 mm, SOD 222 mm
- Prefilter 1 mm Cu
- Voxel size = 33.36 μm

Measured contrast from profile

VisiConsult
(Herold, Buchholz)

Cartesian matrix design
Analysed in a Round Robin Test

VisiConsult
(VisioConsult, Herold, Buchholz)
Computed Tomography: Modulation Transfer Function (MTF)

- Explained and defined in ASTM E1441-19 and ASTM E 1695-20.
- The MTF measurement is performed from the circular profile of the central 2D-slice of a disc or rod.
- The MTF$_{10\%}$ corresponds to the $iSR_{b}^{image}$ of the central 2D-slice.

CT

- Edge response function ERF and line spread function LSF
- MTF vs. $lp/mm$
  - half-logarithmic
- MTF vs. $lp/mm$

Phantom A
The measured relative contrast of the holes is just below the MTF(D*).

In the simulations, the relative contrast values are exactly on the MTF curve.
Computed Tomography: Contrast Discrimination Function (CDF)

• The relative contrast $\Delta \mu / \mu$ is measured in the image of the slice centre and the base area of the air attenuation.
• The noise is measured in the inner 30% of the slice area.
  • The noise measurement is repeated after averaging of the voxels for different voxel sizes.
• The measurement procedure is explained and defined in ASTM E 1441-19 and the latest version of ASTM E 1695-20 (implemented by Volume Graphics in VGStudio).

$$CDF(D^*) \equiv \frac{\sigma_m(\mu_i)}{\bar{\mu}} \times 100\%$$
Computed Tomography: CDD Analysis of the Reconstruction of the Central Slice

- Combined representation of CDD, CDF and MTF with intersection of CDD and MTF at 3.1 voxels.
- The smallest hole, which is just visible, is 78 µm at 25 µm voxel size.
- Marked in bright red is the area where hole indications are visible.

Visibility limit for hole indications with diameter in voxels

Physiological factor for human observers

\[
CDD(D^*) = c \cdot \frac{CDF(D^*)}{MTF\left(\frac{1}{2D^*}\right)}
\]
Round Robin Test –
for New Guideline D7 and ASTM Phantom B - Project

Nine laboratories took part in the Round Robin Test to verify the new phantom design.

- Brasilia 1x
- Germany 5x
- France 1x
- USA 2x

- 50 GByte data.
- Importance of intersection MTF/CDD discovered.
- Accuracy of test specimens needs to be improved.
- Plate combinations (e.g. duplex plates) must be tightly connected.
- VG StudioMax was the only known commercial software, with usable CDD analysis.
- Improvements of algorithm and software proposed.
- Precondition for standardization.
**Duplex Plate-Design**

- Duplex Plate-Design for determining the detectability at different beam lengths

- Duplex Plates with different diameters and same hole patterns.

![Diagram showing Duplex Plate-Design with CNR values for different diameters: CNR = 2.0 (Diameter 60 mm), CNR = 4.5 (Diameter 40 mm).]
Disturbing Effect of Beam Hardening

- Central CT slice of an Al-hole disk of 4 cm diameter.
- The intensity in the profile of the central hole is not zero.

- Central CT slice of an Al-disk of 4 cm diameter.
- The MTF has a maximum at 3 lp/mm.
New Phantom Design with Hole Groups

Modelling with different

Pixel size: 0.2 mm, $\text{SR}_b^{\text{image}} = 0.25$ mm

Magnification: 1.2

Voxel size: 0.16 mm

Internal scatter ratio 5%

Holes:
- 0.25 mm, 0.5 mm, 1.5 mm, 3 mm
- 2 lp/mm, 1 lp/mm, 0.33 lp/mm, 0.167 lp/mm

X-ray, 320 kV
Summary

➢ The **detectability limit** (diameter) of holes and pores in cross-sectional images can be determined by measuring *Contrast Detail Diagrams (CDD)* and *MTFs of cylinder samples* (Phantom A, B).

➢ The detectability limit results from the intersection of CDD and MTF.

➢ The **detectability limit depends** on the beam length and the flaw shape.

➢ **Hardening effects** contribute to a deterioration in recognizability.

➢ **Test plates with separate holes** have been developed and will be standardized to determine the detectability of holes/pores and to monitor the detail sensitivity of CT systems.

➢ **The suitability of the proposed hole plates** was verified within a round robin test.

➢ The procedure will be described in an **ASTM standard and the DGZfP guideline D7**.

➢ The development of new **hole group test plates** is on the way.
The measurement can be carried out together with the test phantom or separately.

Questions... ?

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