Determining the Spatial Resolution in Computed Tomography – Comparison of MTF and Line-Pair Structures

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Abstract. According to the relevant standards, measurements of suitable test pieces are analysed with the two established methods to determine the spatial resolution of CT data (MTF and contrast of line-pairs). The results are compared and differences are discussed.

Introduction

The spatial resolution of a CT measurement is affected by a multitude of factors. Substantial contributions are the properties of the CT device, namely the X-ray source (focal spot size) and the detector (pixel size, scattering), but also the used magnification in cone-beam geometry. The measurement strategy, especially the number of projections per full rotation, and the reconstruction process (voxel size, interpolation, filtering) have a big influence too. Principally, the measurement object also affects the spatial resolution, e.g. by diffraction or refraction of the X-rays, but in the case of the typical laboratory-CT measurements presented here, these are negligible.

The contributions of the single effects are difficult to determine in practice, but from measurements at the reconstructed data set one gets the resulting resolution, considering all effects.

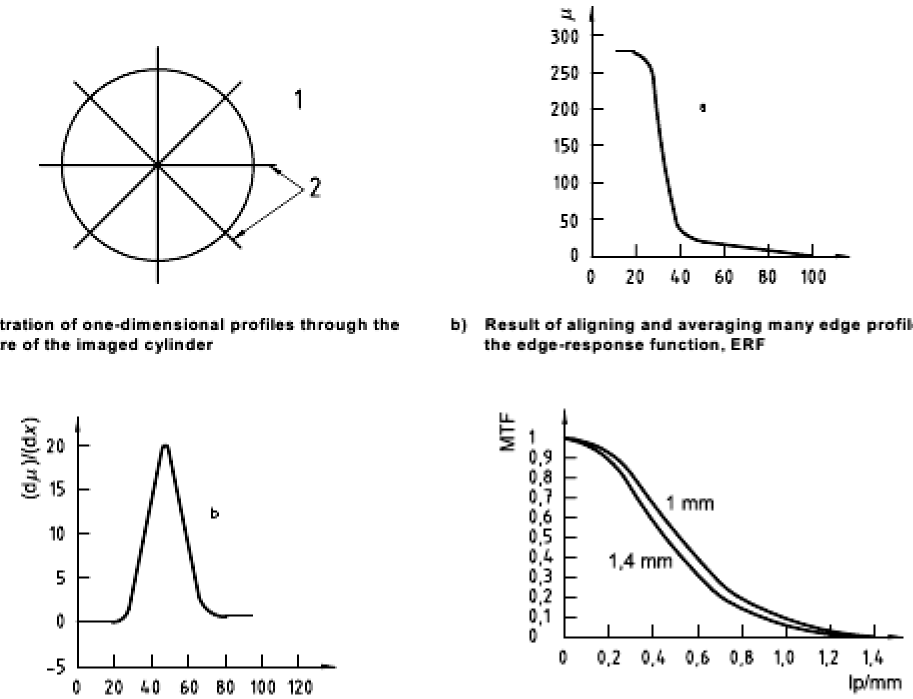
In the following, the two established methods to measure the spatial resolution, MTF and contrast measurements at line-pairs, are introduced. Their application to data sets from test pieces which are suitable for both methods is described and the results are discussed.

1. Determining the spatial resolution

For determining the spatial resolution there are two different possibilities, which are also described in the standards dealing with CT. The first one is calculating the *modulation-transfer function* (MTF) from the measured edge of a cylinder, the second one is measuring the contrast of material to background in dependence on the size of the structures of line-pairs.

1.1 Calculation of the MTF

The MTF is the contrast amplitude in dependence on the spatial resolution. In the standard ISO 15708-2:2002 it is shown how to calculate it from the measurement of the edge of a cylinder (Figure 1):



a) Illustration of one-dimensional profiles through the centre of the imaged cylinder

b) Result of aligning and averaging many edge profiles, the edge-response function, ERF

c) System line-spread function, LSF, obtained by differentiation of the ERF

d) System modulation-transfer function, MTF, obtained by discrete Fourier transformation of the LSF for two different resolution aperture settings

Figure 1. Determination of the MTF from the edge in the reconstructed CT data set of a cylinder (from ISO 15708-2:2002)

Profiles are calculated along lines through the centre of the measured cylinder (a), and the edge-response functions (ERF) are calculated. From the averaged ERF (b) the line-spread function (LSF) is determined by differentiation of the ERF (c). Via Fourier-transform the MTF is calculated from the LSF (d).

An alternative approach to calculate the MTF directly from the ERF is described in [1]. In the case of the measurements analysed here, both methods gave nearly identical results.

Following convention, the MTF is normalised to One and given in line-pairs per millimetre (LP/mm).

1.2 Determining the spatial resolution from line-pair structures

As alternative to determining the spatial resolution by calculating the MTF, the standard FprEN 16016-3:2010 (document CEN/TC 138 N 1153, Annex A) mentions the calculation of a contrast factor R as function of the resolution, measured at line-pair structures. In this standard, line-pair structures are presented which are structures alternating between material and air, and which have quadratic shape and equal width. These are manufactured into cylinders with a diameter of 65 mm (Figure 2).

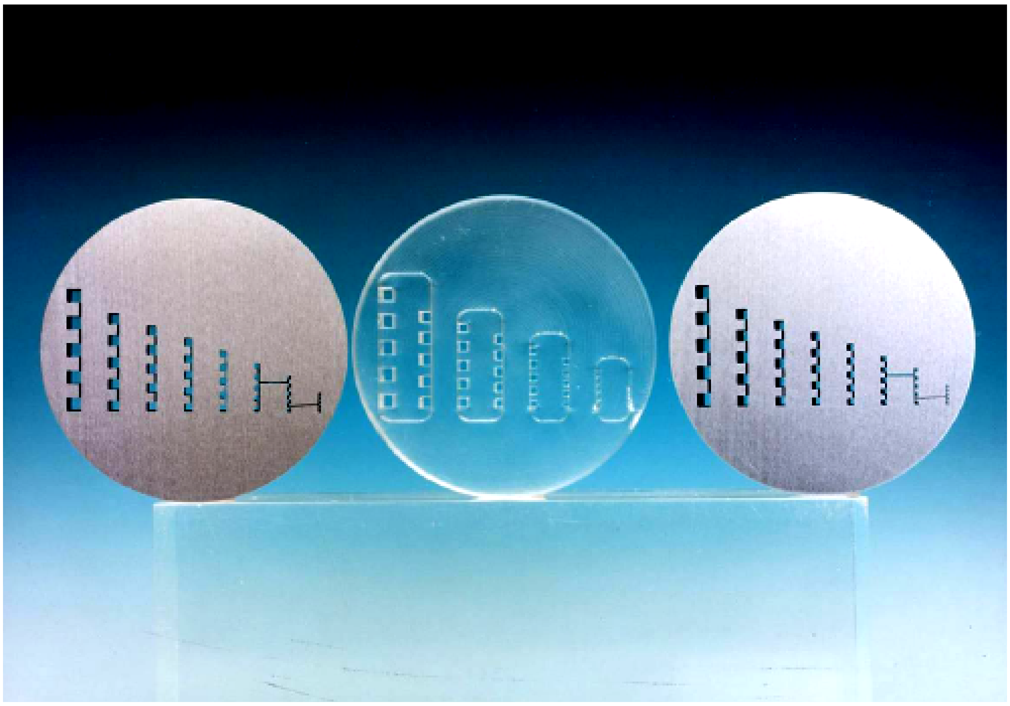


Figure 2. Test pieces with line-pair structures (from left to right: made of aluminium, acrylic glass, and steel; from FprEN 16016-3:2010)

The eight different structure sizes range from 0.4 mm to 2.5 mm, corresponding to a spatial resolution of 1.25 LP/mm to 0.2 LP/mm, respectively.

The contrast is measured at a grey-value profile along a line in the reconstructed volume, where the grey-value minima $N_A(i)$ are determined in the cut-outs, and the maxima $N_B(i)$ in the material bridges (Figure 3).

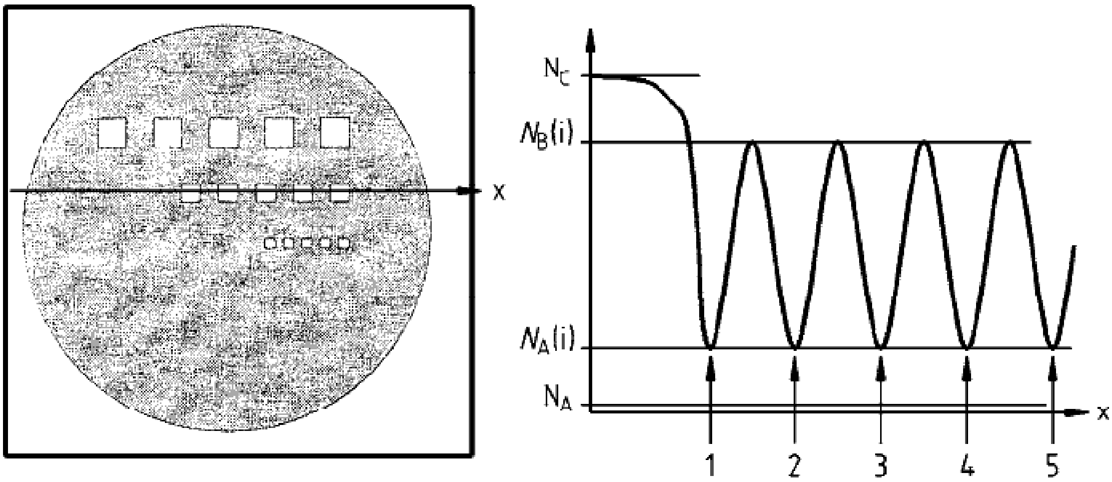


Figure 3. Determination of grey-value extrema at the line-pair structures (from FprEN 16016-3:2010)

The contrast-factor $R(i)$ is the difference between $N_B(i)$ and $N_A(i)$, normalised to the grey-value difference of the undisturbed material N_A and the undisturbed background N_C, multiplied by 100 (Equation A.1 in FprEN 16016-3:2010):

$$R(i) = \frac{N_B(i) - N_A(i)}{N_C - N_A} \times 100$$

3. Comparison of both methods

The test pieces shown in the standard FprEN 16016-3:2010 are cylinders with cut-out line-pair structures. Therefore they are suitable for determination of the spatial resolution with both methods described above. The measurements presented in the following were performed at the test pieces made of brass and aluminium shown in Figure 4, which were machined at BAM.

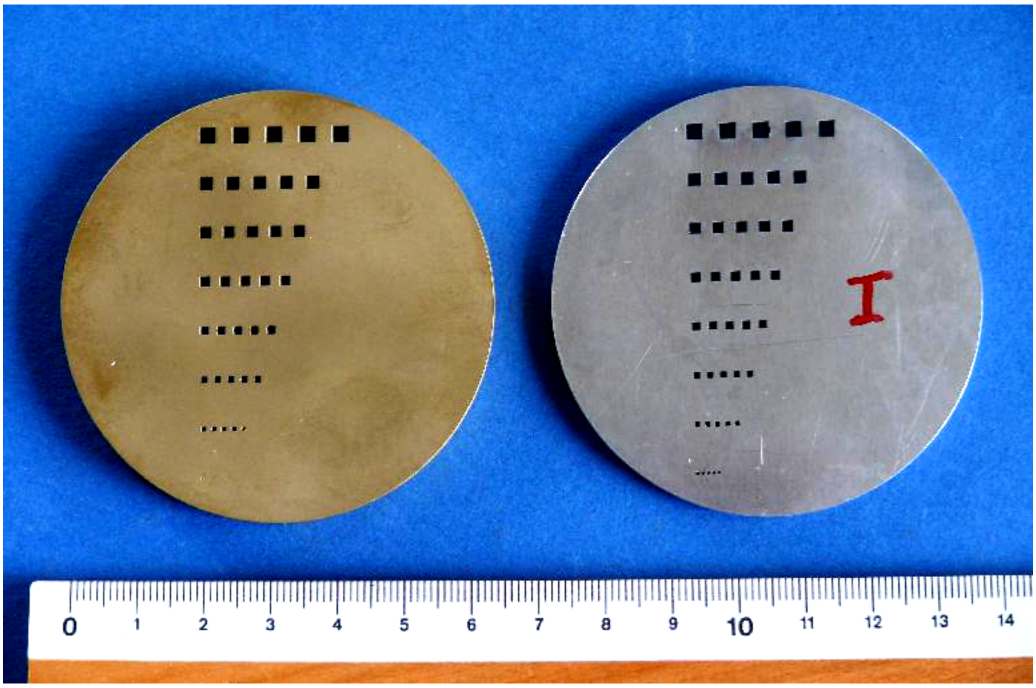


Figure 4. The test pieces machined at BAM, made of brass (left) and aluminium (right)

3.1 Measurement at the brass test piece

The brass test piece was measured with the BAM 12-MeV-Linac. A pre-filter of 20 mm iron was used, the magnification was 1.38, and the resulting voxel size is 0.145 mm. For the analysis the data set was reconstructed in such a way, that the line-pairs are aligned to the voxel grid. To study the influence of an applied beam-hardening correction (BHC) on the measured spatial resolution, both, the original and the beam-hardening corrected data set were analysed.

For being able to determine the MTF from the cylinder's edge-profile, the centre of the cylinder was determined by fitting a circle to the outline of the cylinder in the considered slice perpendicular to the cylinder axis. Along different lines through the centre, grey-value profiles were calculated, averaged, and used for the calculation of the MTF.

In the chapter of FprEN 16016-3:2010 concerning the determination of the spatial resolution from line-pair structures it is written that no line-profiles shall be averaged. ("These two values are measured using a grey-level profile determined along the hole axis and unaveraged."). This point is insofar puzzling, as for averaging line-pair structures aligned to the voxel grid no resolution-decreasing interpolation is necessary. Instead a higher signal-to-noise ratio can be achieved and the influence of the user (selection of one specific profile) will be reduced. For the following analysis averaged line-profiles were used.

Additionally, the standard does not specify how the single extremum values are to be determined. In the case of the data set analysed here, fitting Gaussian curves to the maxima and minima seems to be the correct way (Figure 5).

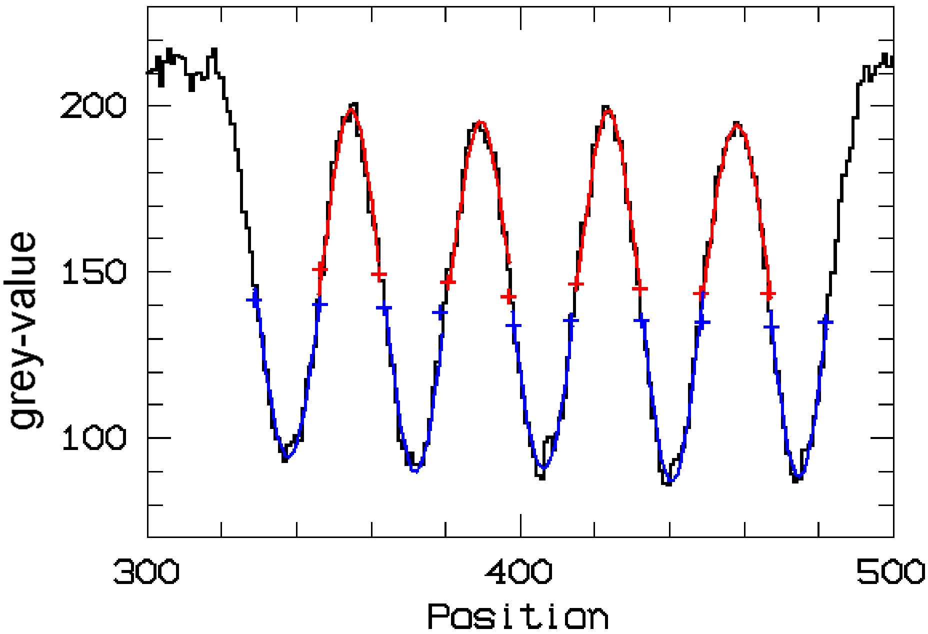


Figure 5. Gaussian curves fit to the maxima (red) and minima (blue) of an averaged line-profile

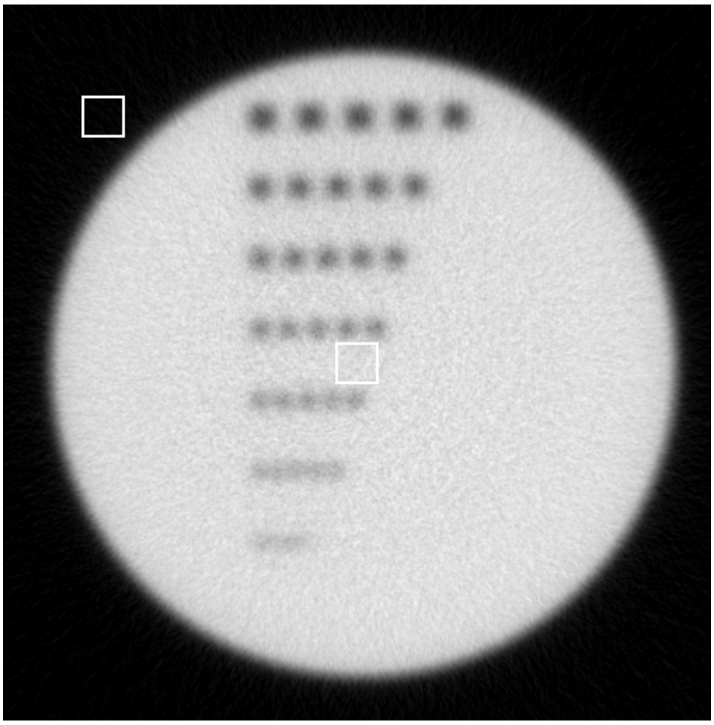


Figure 6. Location of the regions for determining the grey-values of the undisturbed material and background

By averaging the maximum values of the Gaussian curves one obtains the values $N_B(i)$ as input for the calculation of R, likewise the $N_A(i)$ from the minima. The regions for measuring the grey-values of the undisturbed material N_A and of the undisturbed background N_C, which are needed for the normalisation, are marked in Figure 6.

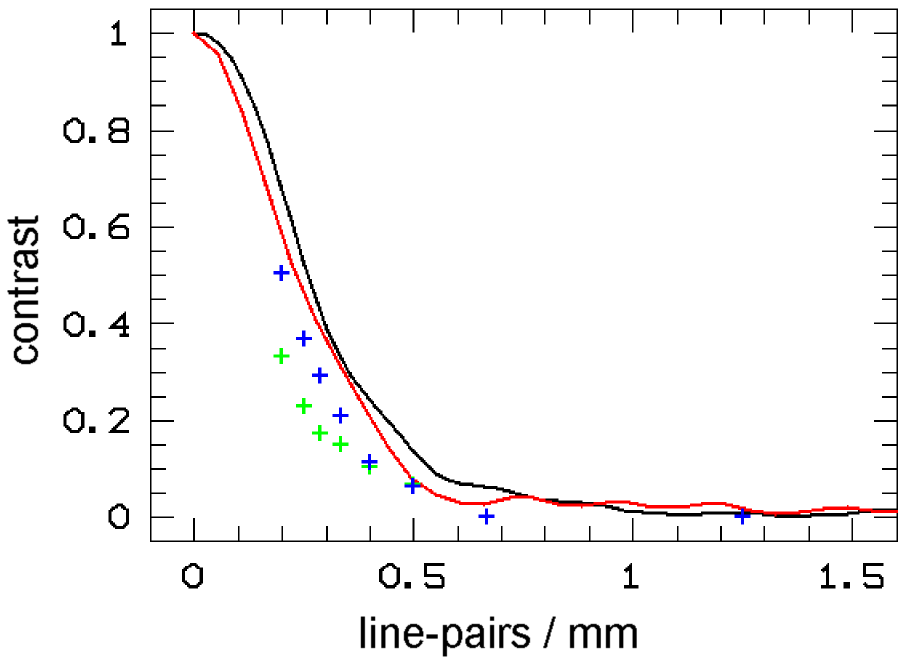


Figure 7. MTF determined at the brass test piece (black: without beam-hardening correction (BHC), red: with BHC) and contrast-factor R/100 (blue: with BHC, green: without BHC)

Figure 7 shows the results of the measurement of the spatial resolution at the brass part. For comparison with the MTF, $R/100$ is shown, and the resolution is given in LP/mm.

The behaviour of both MTFs is nearly identical, meaning that the BHC doesn't have much influence on them for this data set. The R-values from the line-pairs are significantly lower than the corresponding MTF values, and there is a big difference between the two measurements of R. These differences are originating from the different normalisation schemes, where the MTF is in the last calculation step normalised to one, whereas R is normalised to the grey-value difference of undisturbed material to undisturbed background. Additionally, scattered radiation and beam-hardening affect the grey-values inside the test piece, causing especially those in the cut-outs to considerably deviate from the expected ones.

3.2 Measurement at the aluminium test piece

The measurement at the aluminium test piece was carried out at the BAM 225 kV-CT-device. The acceleration voltage was set to 200 kV, a pre-filter of 1 mm of copper was used. The magnification was 5.6, the resulting voxel size is 35.8 µm, which is much larger than the estimated extent of the focal spot of around 8µm. This data set has been analysed also with and without BHC.

After determination of the cylinder centre in the middle plane of the measurement (Figure 8), the MTF was calculated from the averaged edge-profile.

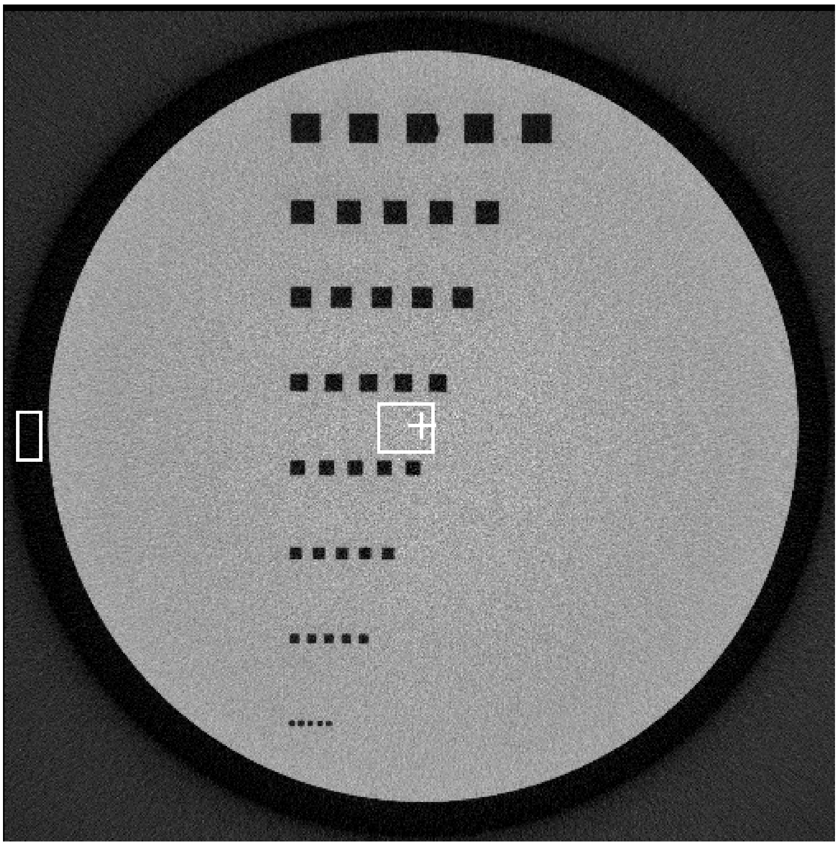


Figure 8. The reconstructed data set of the aluminium part with applied BHC. The centre of the fitted circle and the regions for determining the grey-values of the undisturbed material and the undisturbed background are indicated.

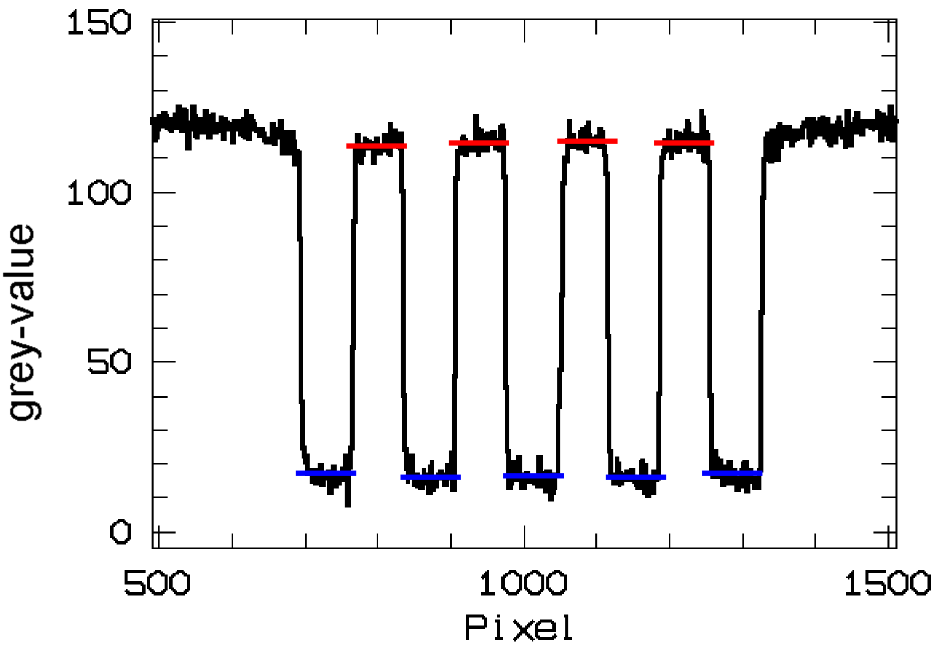


Figure 9. Determination of the minimum (blue) and maximum values (red) at an averaged line-profile from the measurement of the aluminium part

For the determination of the spatial resolution, multiple line-profiles were, again, averaged to get a better signal-to-noise ratio. In the case of this measurement the line-profiles show a rectangular modulation. It is, therefore, not suitable to fit Gaussians to the extrema, but to determine the local extremum values by fitting lines instead (Figure 9).

By averaging the individual maxima respective minima, the values $N_B(i)$ and $N_A(i)$ are obtained. The regions for the determination of the grey-values N_A and N_C needed for the normalisation are indicated in Figure 8.

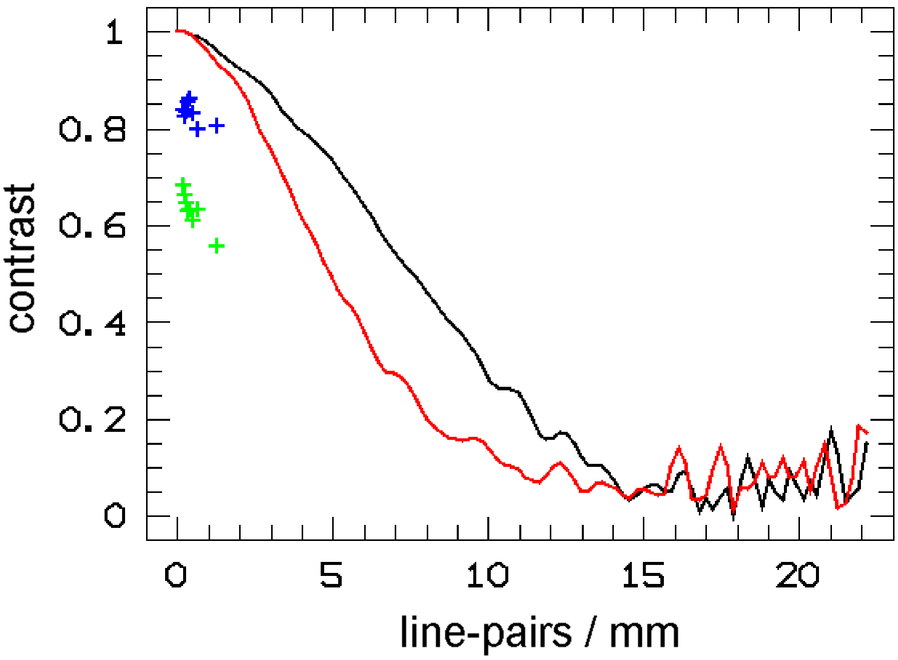


Figure 10. Results of the measurement of the spatial resolution at the aluminium part data set (black: MTF without BHC, red: MTF with BHC, blue: R/100 with BHC, green: R/100 without BHC)

Figure 10 shows the results of the spatial resolution determination at the measurement of the aluminium test piece. The MTF determined at the not beam-hardening corrected data set (black curve) reaches the contrast value of 0.2 at a resolution of 11 LP/mm, which is with 1 LP per 2.5 voxels close to the theoretical maximum resolution. Striking is the big difference to the MTF from the BHC data set (red curve). A possible explanation for this difference lies in the modification of the grey-values in the projections when applying the beam-hardening correction. The pixels only partially covered by the object have a much higher grey-value than those completely covered next to them, which still have a similar attenuation length. They are thus much stronger modified by the beam-hardening correction, because they are considered as regions of small penetrated length. This leads to a large scatter in the edge's grey-values and thus to an unsharp reconstruction of the cylinder's surface, resulting in lower MTF-values.

The values of R determined at the line-pair structures are clustering close to resolution zero and do not reach a region where they could give information on the measurement's spatial resolution, e.g. if one considers contrast values of 0.2 or 0.5 as "the resolution of the measurement".

Once more it becomes clear that the values of the MTF and R are not directly comparable.

4. Summary and discussion

The instructions for determining the spatial resolution with line-pair structures in the standard FprEN 16016-3:2010, according to which the resolution was measured here, are formulated quite vague and leave much room for interpretations. It is not clear, why the profiles through the reconstructed line-pair structures shall not be averaged, which would increase the signal-to-noise ratio. It is not specified how the maxima and minima in the profiles are to be determined. Furthermore there is a typo: The grey-value for the background material shall be determined in a region "*located at the centre of the reference part*". This part of the standard (Annex A) should be revised.

When comparing the MTFs and contrast-factors R determined at identical data sets, it becomes obvious that line-pairs are not the best choice for measuring the spatial resolution of micro-CT devices, because structures with sizes much lower than one millimetre can be machined only with difficulties or not at all, depending on the material. On the contrary it is quite easy to produce a cylinder of sufficient accuracy and to use it for the determination of the MTF. As test pieces for macro-CT devices, line-pairs yield nearly identical contrast values as the MTF from the edge of a cylinder.

The seemingly worse values of the contrast-factor R compared to the ones in the MTF are mainly caused by the different normalisation approaches. Furthermore, the grey-values inside the test piece are affected by scattered radiation and beam-hardening, which reduce the contrast of material and background.

Applying a beam-hardening correction to the data sets does not influence the determination of the MTF if the size of the X-ray tube's focal spot is much larger than the detector pixels scaled to the centre of rotation. In the case of significantly smaller focal spots, as they are present in micro-CT devices, the beam-hardening correction is reducing the spatial resolution measured with the MTF because of changes in the grey-values of the cylinder's outer edge.

The biggest challenge on the way to a meaningful MTF from the edge of a cylinder is the determination of the cylinder's centre with a very high accuracy. If profiles through a wrong centre point were averaged, the edge would become blurred.

In both measurements shown here, the test piece was placed nearly centred on the rotational axis in the middle plane. Thus the eventually present positional and directional dependence of the spatial resolution has not been addressed here. It also has to be noted that the resolution is determined in different distances from the rotational axis using the cylinder edge or the line-pairs.

References

[1] Schneiders, N. J. & Bushong, S. C.: Single-step calculation of the MTF from the ERF, Medical Physics, 1978, 5, 31-33