Physics and special technology of very fast or even inline industrial 3D-CT

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Abstract

3D computed X-ray tomography, in short 3D-CT, has evolved so rapidly in recent years and made such strides in acceptance and distribution, that it is now considered a standard procedure in production environments. The benefits of 3D-CT compared with long-established 2D X-ray methods are obvious, as 3D-CT provides much more information than conventional 2D methods. It not only allows the simple detection of structural defects and characteristics of components, but can also determine their location, size, and shape more precisely than 2D methods. Furthermore, 3D-CT can determine the wall thickness of components and do nominal/actual comparisons using CAD data. In general, CT provides information about the size accuracy of a component, even in hidden and internal structures. It is exactly this wide range of application possibilities that predestines 3D-CT as a universal, non-destructive inspection method whose advantages are transferred to production. In order implement such inspections, both the measurement and the fully automated evaluation must take place in time with the extremely short production cycle. This paper describes the relevant physical parameters for CT measurement and the effect a short measurement time has on the measurement and feature extraction of the components being tested.

Keywords: 3D-CT, inline, X-ray, industry, NDT, production

1 Basics of 3D-CT

With conventional radiographic testing, the attenuation profile of the 3D object being tested is projected onto a 2D recording medium so that the consecutive images projected in the direction of transmission overlap. No information is provided about the exact location of the object details. Therefore, it may be necessary to X-ray the object from multiple directions and compare and correlate the resulting images in order to evaluate them. However, for a complex object structure, this can be very difficult if not impossible. Therefore, methods were developed to reconstruct object layers from X-ray scans using mathematical methods that allow for simple evaluation.

The most popular procedure for reconstructing object layers is computed tomography (CT). This usually involves scanning the object from 360° and recording the individual attenuation profiles, i.e. projections, from different directions. When passing through the object, the monochromatic X-rays are weakened according to the Beer-Lambert law:

\[ I = I_0 \cdot e^{-\int \mu(x) \cdot ds} \]
The detector registers the weakened intensity detected from the projection $P$:

$$P = \ln\left(\frac{l_0}{l}\right) = \int_{x} \mu(x) \cdot ds$$

By means of mathematical reconstruction methods, these projections can be used to calculate a corresponding object layer. The most commonly used method for this is the so-called filtered back projection. Radon described the mathematical foundations for this in as early as 1917 [1]. Various numerical methods allow for the fast calculation of object layers and 3D data sets using a PC [2, 3, 4].

The following illustration shows the principle of data acquisition using CT with parallel beam geometry:

Figure 1: Principle of CT data acquisition.

Today, not 2D, but 3D-CT is used in most cases to record 2D projections using a flat detector.
Various difficulties can arise in the technical implementation, such as the fact that the Beer-Lambert law in the abovementioned form only applies to monochromatic radiation. However, with the use of X-ray tubes, a complete polychromatic spectrum (Bremsstrahlung) is used. Since the X-ray tube energy range of approximately 30 keV to maximum 600 keV of the attenuation coefficient decreases above the K-edge for increasing energy, the low-energy part of the spectrum is weakened more than the high-energy part when passing through the object. This is called beam hardening and leads to artifacts in the reconstructed data record. Even more artifacts can be created when incomplete angle ranges are scanned, the number of projections is too low or the object is partially outside of the beam [5]. Noise can also greatly limit the quality of the reconstruction [6].

2 Resolutions

Indeed there are several kinds of resolution we have to have a look at in the following chapters to fully understand 3D-CT.

2.1 Spatial Resolution

Various parameters influence the spatial resolution of a CT imaging system. It is defined as the minimum distance between two greatly contrasting, point-shaped objects which can still be perceived as being separate. This is described by the Modulation Transfer Function (MTF), or its Fourier transform, the Point Spread Function (PSF) [7, 8].
Figure 3: Remaining signal of two neighboring point-shape objects.

The main factors influencing spatial resolution are shown in the following illustration:

![Focused tube diagram](image)

Figure 4: Blurring caused by focal spot and magnification.

For a selected geometry with a magnification $M = b/a$, the finite geometric expansion of the focus of the X-ray tube produces a blurring of a discrete point or an object edge of:

$$U_{FS} = d \cdot \frac{b - a}{a} = d \cdot (M - 1)$$

This value refers to the level of the detector, resulting in the following for the image or object layer:

$$U_{FS} = d \cdot \frac{(M - 1)}{M}$$

This means that for large magnifications in which $(M-1)/M$ adopts a value in the range of approximately 1, the spatial resolution is determined by the size of the focal spot.

Small magnifications, on the other hand, i.e. when the object is positioned close to the detector, the resolution is determined by the finite width of the detector elements. Two details can then only be perceived separately when they are not projected in adjacent detector elements. The projected distance...
must be at least 2 $d_{\text{det}}$ if the width of the detector is 1 $d_{\text{det}}$. The occurring blurring in the object layer is therefore:

$$U_{\text{Det}} = \frac{2d_{\text{Det}}}{M}$$

In addition to the focal spot and the detector size, which are the most dominant influences, there are also other influences to consider, such as the temperature drift of the components, mechanical inaccuracies of the manipulation system or arising artifacts that become noticeable in an additional blurring $U_{\text{xxx}}$ but which we will not discuss further here. All in all, we have a total system blurring of:

$$U_{\text{total}} = \sqrt{(U_{FS})^2 + (U_{\text{Det}})^2 + (U_{\text{xxx}})^2}$$

The voxel size is usually chosen to equal half of $U_{\text{total}}$. In this way, should two details be projected in voxels not directly adjacent to each other, they can also be perceived separately. Because of the total system blurring, smaller voxels would not lead to a better resolution and larger voxels would restrict the resolution even more.

### 2.2 Contrast Resolution

In addition to the spatial resolution, the contrast resolution of an imaging system such as a CT must be especially considered. This is at least as important as spatial resolution, if not more so. After all, object details must first be detected before their exact size can be determined and other evaluations conducted.

The contrast resolution of a CT is greatly determined by the effective dynamic range of the detector being used. This is defined by the number of theoretically resolved gray values (e.g., 12-, 14- or 16-bit) divided by the residual noise of the detector electronics.

![Contrast resolution determined by detector dynamics.](image-url)
If the resulting gradation, i.e. detector dynamics, is too low, small differences in thickness can no longer be perceived.

In computed tomography, rotating the object allows the x-rays to pass through even very small object thicknesses, especially at the edges and corners, as well as the maximum diameter of the object, i.e. the maximum total wall thickness. Therefore, the dynamic of an X-ray detector necessary for CT is always much higher than the dynamic necessary for a 2D-inspection in which the object is ideally aligned.

In practice, the actual limitation of the contrast resolution is often not determined by the depth of digitization, but rather the noise. If the signal-to-noise or the contrast-to-noise ratio (SNR or CNR) isn’t large enough, small and low-contrast details will inevitably get lost in the noise.

Noise can be caused by scattered radiation and detector noise, but also an insufficient number of detected X-ray photons. Low X-ray power in particular often leads to very bad photon statistics and one can more or less see the Poisson noise of the X-ray tube.

3 Requirements in a Production Environment

Incorporating a fast 3D-CT system in a production line comes with an array of unique challenges, all of which are closely tied to what was previously mentioned. The usually very short production cycle, in particular, is just one of these challenges. For a laboratory inspection system, it is completely acceptable if a CT scan takes between 15 minutes to an hour, depending on the resolution. Production, on the other hand, typically requires a scan in less than 60 seconds. Cycle times (and thus scan times) of 15 to 30 seconds are the norm for the inspection of light alloy castings or plastic components, for example.

Furthermore, the hardware of a 3D-CT system must be robust, able to run 24/7, and require little to no maintenance in order to avoid stoppages and downtimes. The initial investment costs also play an
important role and must not be too high in order to minimize the test cost per component. All of this must be considered when putting together a concept.

4 Consequences for 3D-CT Measurement

The very short time available for measuring as described above leads to a dramatic reduction in detected X-ray quanta in comparison to a CT scan in a laboratory and thus a very poor SNR. This must be counterbalanced so that the object characteristics of interest can still be detected.

4.1 Collimation

A reduction in noise is often achieved by maintaining a fixed distance between the X-ray source and detector. This allows a fixed collimator to be installed, which limits the X-ray cone beam to the active area of the detector, thus minimizing scattered radiation that would otherwise come from the cabin walls and sample manipulator.

4.2 X-Ray Energy and Performance

Furthermore, relatively high X-ray energies are used and the X-ray beam is strongly pre-filtered directly at the exit window of the X-ray tube. This reduces the amount of low-energy X-ray radiation that, in any case, can only penetrate the object with difficulty and contribute to strong beam hardening artifacts. These are reduced, which in turn facilitates an automated analysis. Simultaneously, the filtered low-energy radiation no longer contributes to the Compton Effect produced in the object, which also reduces the amount of noise in the scans.

Also, this approach exploits the well-known fact that, while the generation of X-rays in a tube increases linearly with the tube current, i.e. the tube power, it increases squarely with the tube voltage. Therefore, if one increases the latter and thus the X-ray energy, one will generate a square-law X-ray output with only a linear increase of the electrical power of the tube.

4.3 X-Ray Tube

In turn, the electrical power of the tube is important for the size of the focal spot. Small focal spots and thus a high attainable spatial resolution are only possible for small tube powers [5]. In order to produce enough X-ray photons for a reasonably acceptable SNR despite the short measuring time available, closed X-ray tubes with high output and large focal spots are almost exclusively used at this point in time, with the object placed closer to the detector. While the attainable spatial resolution is thus primarily determined by the detector pitch $d_{det}$ and definitely far worse than when using micro-focus equipment in a lab setting, such tubes are also low maintenance, durable, and less expensive, which in turn supports the goal of reducing test costs per object.
4.4 X-Ray Detector

The final component relevant to imaging left to consider is the detector. Based on the aspects previously discussed, it is obviously very important to use a detector with high sensitivity, i.e. quantum efficiency, and low noise. In fact, flat panel detectors (aSi or CMOS) with CsI scintillators are used almost exclusively in the fast 3D-CT systems described. Due to the needle structure of CsI, these scintillators can be substantially thicker at the same resolution than, e.g., traditional Gadox-based films. In contrast to 2D-testing, the well-known afterglow effect of CsI at high X-ray energies plays a subordinate role in 3D-testing, during which a variety of projections from every direction are calculated together, so that this afterglow in substance averages out. The advantage of the significantly higher quantum efficiency greatly outweighs the disadvantage of a remaining light background in the reconstruction. While direct converting detectors theoretically have an even higher quantum efficiency, they usually have insufficiently large active areas and simply are too expensive.

When it comes to selecting detector resolution, i.e. the pitch size, one must remember that when using a high-power tube such as described, the spatial resolution is determined by the detector. On the other hand, a detector pitch that is too small can greatly increase the amount of noise in the reconstruction. If the same detector type with a detector pitch that is half the original size is used in otherwise identical conditions (tube, distance, current, voltage, integration time...), such as a (2k)² detector instead of a (1k)² detector of a certain design, the original area of a detector element is now spread across 4 pixels. Each individual pixel now only receives a quarter of the photons and, accordingly, only one-eighth of the photons are reconstructed in each 3D-voxel, since a voxel is divided into eight by half of the edge length. In order to get the same SNR in 3D, it would need to be exposed eight times as long. The lower fill factor of the detector elements and the usually higher noise of detector electronics of higher-resolution detectors have yet to be taken into account.

Therefore, it should be noted that in such cases, the spatial resolution can once again only be gained at the cost of the already critical contrast resolution. Therefore, one must be sure to select a detector that achieves the spatial resolution required for the specific inspection task without significantly exceeding it.

4.5 Inspection Implementation

In summary, every 3D-CT inspection in a production environment must be tailored and adapted to the inspection task at hand in order to achieve the best possible results. There are conflicting influences and requirements that are physically linked by the number of detected photons. Therefore, in a sense, every inspection task simultaneously represents an optimization task that has to be solved. This relationship can be illustrated in a so-called X-ray inspection pyramid [9].
5 Automated Inspection

Of course, a 3D-CT data set must not only be measured and reconstructed in the production cycle, but also automatically evaluated. It is imperative for the acceptance of such inspection systems that the users can create the inspection procedures themselves, without the help (and cost) of external service providers, as well as reconfigure them at any time for other applications. Because of the generally poor SNR, all analyses must be much more configurable than generally required for a standard laboratory system. Only so can the users react to different image qualities and adapt the analyses accordingly. It goes without saying that all analyses are automated, combinable, and able to be tolerated, so that nothing stands in the way of an automated evaluation ending in an automatic good-bad decision.

For series testing, the opportunity arises to incorporate an analysis tool that is explicitly tailored to the realities of repetitive, identical measurements with short measuring times. To this end, one must first create a virtual “Golden Part” which is created out of a defined minimum number of measured parts that have been classified as “good” (usually >100). This “Golden Part” is then used as a reference data set. This allows one to define, with sufficient statistical confidence, what a “good” part should look like and which deviations on which parts are considered normal. The advantage here is that even the image artifacts that inevitably arise in a CT scan and can sometimes cause problems in conventional analysis methods are trained. Such reference data sets can usually be built using data from a single production shift. Then, the actual inspection only consists of a complete volumetric nominal/actual comparison. This can compare grey values in the reconstructed data set as well as more complex features like fiber orientation. This method is not only much faster than conventional analysis methods, but also incomparably sensitive and less error-prone. Therefore, this method should always be considered for automated testing when none of the influential factors relevant for the CT are changed and traditional methods are not sensitive or fast enough due to artifacts or noise.
In general, every automatic evaluation must be easily scalable. In other words, should an evaluation take longer than the preset production cycle when run on a single evaluation computer, more evaluation computers must be able to be easily incorporated. This is also necessary in case a computer is lost due to a technical defect. Software should be able to autonomously distribute the calculation tasks without requiring input from the user. This is the only way to guarantee redundancy and reliability, both of which are imperative in production.

6 Summary

The widespread use of 3D-CT in production as a powerful inspection procedure continues to gain in acceptance. Meanwhile several dozens of inline-CT systems have been installed in production. Of course, the unique conditions, particularly the short measurement time, require the ability to adapt the system hardware and the evaluation software to the characteristics of production as described at length above.

References