

Industrial Applications of Dual X-ray Energy Computed Tomography (2X-CT)

T. Fuchs, P. Keßling, M. Firsching, F. Nachtrab and G. Scholz

Abstract The Fraunhofer Development Center X-ray Technology (EZRT) developed an industrial dual-energy X-ray Computed Tomography (2X-CT) system in order to obtain quantitative 3-D information on the material inside arbitrary samples. The goal was to develop an easy-to-use dual-energy solution that can be handled by the average industrial CT operator without the need for a specialist. First, an introduction is given of the physical background of the method that was realized. Also, the strengths and weaknesses thereof are discussed. Next, the results of 2X-CT measurements from different fields of investigations are presented: measurements with vegetables, e.g. potatoes or bananas, quantitative assessments of bore cores in geological applications, and studies of carbon fibre reinforced plastic (CFRP). In summary, it is shown that 2X-CT can provide accurate information about the composition of a wide range of materials and objects. On the other side, there is still the need for further optimization of X-ray parameters in order to increase quantitative accuracy, and for extending the range of materials which can be assessed by industrial 2X-CT.

Keywords Computed tomography • Dual x-ray energy • Industrial application • Material analysis • Quantitative 3-D imaging

Motivation

Dual-energy Computed Tomography is an established method in the field of medical CT to obtain quantitative information on bone mineralization or calcifications in a human patient - instead of mean attenuation coefficients or grey values only. Up to

T. Fuchs (✉) • P. Keßling • M. Firsching • F. Nachtrab • G. Scholz
Fraunhofer Development Center X-ray Technology EZRT,
Dr.-Mack-Str. 81, 90762 Fürth, Germany
e-mail: theobald.fuchs@iis.fraunhofer.de

now, in the field of industrial X-ray imaging dual-energy techniques have been used to solve particular problems on a case-by-case basis rather than as a standard tool.

The goal of the presented work was to develop an easy-to-use dual-energy solution that can be handled by an average industrial operator without the need for a specialist. The actual dual-energy analysis tool is called *2X-Suite* [1]. In cases where qualitative measurements are not sufficient, it provides additional quantitative information (e.g. mass density) about the sample at hand.

Theory and Method

The *2X-Suite* is based on an algorithm proposed by Heismann et al. for application in medical CT [2]. As input data this algorithm needs two CT data sets, one with a low (LE) and another with a high effective X-ray energy (HE). A first order linearization is applied to the raw data, and two volumes are reconstructed thereafter. The dual-energy analysis is done voxel by voxel, using a pre-calculated function:

$$F(Z) = \frac{\mu_{LE}}{\mu_{HE}} \quad (1)$$

$F(Z)$ accounts for the different interaction probabilities of the X-rays with the material at the low resp. high energy and therefore depends on the parameters of both measurements (such as tube voltage, filtration and detector sensitivity). As a result, two volume data sets are obtained, one giving the mass density ρ (in g/cm^3) in each voxel, the other providing the effective atomic number Z_{eff} of the material therein. Thereby every pair of measurements of the attenuation coefficient at different effective energies (μ_{LE}, μ_{HE}) is transformed to another basis, e.g. the density ρ and atomic number Z of the materials contained in the sample:

$$\begin{pmatrix} \mu_{LE}(\rho, Z) \\ \mu_{HE}(\rho, Z) \end{pmatrix} \rightarrow \begin{pmatrix} \rho(\mu_{LE}, \mu_{HE}) \\ Z(\mu_{LE}, \mu_{HE}) \end{pmatrix} \quad (2)$$

One important difference between medical and industrial CT is that the range of materials occurring in a sample is much wider in the latter case, and can cover almost the full range of chemical elements. Heismann's algorithm is limited to a range of elements from $Z = 1$ to 30, which seems very suitable for medical applications but is not enough for most industrial materials.

Therefore the possibilities of extending the afore mentioned approach to dual-energy imaging to a wider range of materials were investigated. For $Z > 30$ the function $F(Z)$ as given by Heismann is not a bijective function anymore.

By varying the parameters like e.g. the material and the beam filtration, it is possible to obtain different functions $F(Z)$, allowing the inversion of the function for different ranges of Z . Especially the influence of different detectors (exhibiting

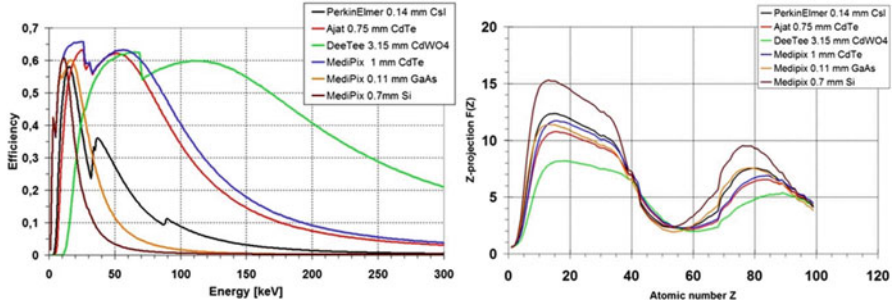


Fig. 1 Comparison of different sensor efficiencies (left) and influence of different sensor efficiencies on $F(Z)$ (right)

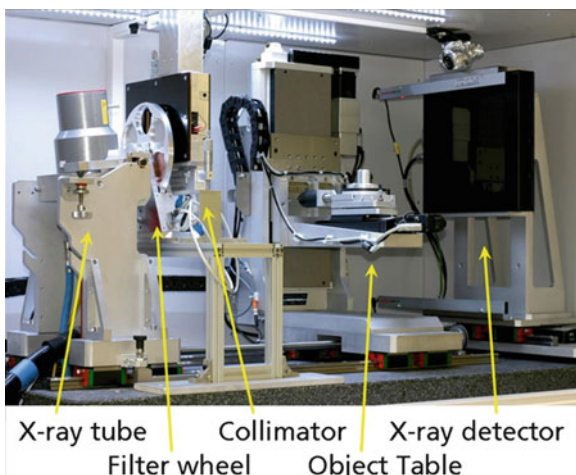
different sensor sensitivities) on the $F(Z)$ function is of note. The efficiency of several detectors was simulated using models of these detectors with the Monte-Carlo X-ray simulation tool ROSI [3]. Simulated efficiency curves and the influence of the detectors on $F(Z)$ are shown in Fig. 1.

In addition, the projection function $F(Z)$ is influenced by many parameters: the high- and low-energy tube voltage, filter materials and filter thicknesses for the high- and low-energy spectrum and the detector sensitivity. Thus, a database was built up including all data needed for the calculation of $F(Z)$ like material parameters (attenuation coefficients, density), and descriptions of tubes (spectra) and detectors (spectral sensitivities). A numerical tool was implemented allowing a quick forecast of different setups and measurement situations. With these tools, the CT operator is enabled to analyze systematically the influence of the different parameters on the projection function $F(Z)$. Having this knowledge, a projection function for a certain range of materials which shall be distinguished can be ‘tailored’.

Equipment

The realized setup consists of a commercially available CT-machine which was equipped with specially chosen components and upgraded with self-developed hardware (see Fig. 2). The X-ray source is a 225 kVp minifocus tube with a maximum power of 1.8 kW. A computer-controlled filter wheel is used to automatically change filter packs to modify the spectrum. A motorized collimator is used to reduce the cone beam diameter in order to suppress scattered radiation. An accurate manipulation system is used to place the object in the beam and to rotate the object for CT data acquisition. The image is recorded using an indirectly converting flat-panel detector, the Perkin Elmer XRD 820 CN14 (200 μm pixel, 1024^2) with a carbon entrance window to enhance low energy detection efficiency.

Fig. 2 Experimental setup of the 2X-CT system including the wheel to remotely change the filtration and a multi-purpose collimator



Results

Application in Biology

Figure 3 shows the measurements of a banana as an example for a dual-energy measurement with ρ - Z_{eff} -projection. It is remarkable, that the chemical composition given by Z_{eff} is very homogeneous (Fig. 4), with nearly constant values close to that of water (approx. 7). The X-ray parameters were 80 kV, 1.5 mA, and 1 mm Al, respectively 120 kV, 3.0 mA, 1 mm Cu for the LE and HE data set.

Geological Sample

Another task 2X-CT was used for is the assessment of bore cores (e.g. from sand stone or granite) to quantify mineral contents. One example is a Gneiss pebble of about 6 cm in diameter. The resulting Z_{eff} varied around 8.4, while from theoretical calculation about 11 was expected. ρ was measured as 2.6 g/cm³ with 0.1 g/cm³ standard deviation. The reconstructed sections (Fig. 5) show, that the metamorphit has a rough internal structure, due to the geological processes creating this kind of natural rock. Data acquisition was made with 120 kV, 0.75 mA, 2 mm Al for LE and 200 kV, 1.75 mA, 2 mm Cu for HE.

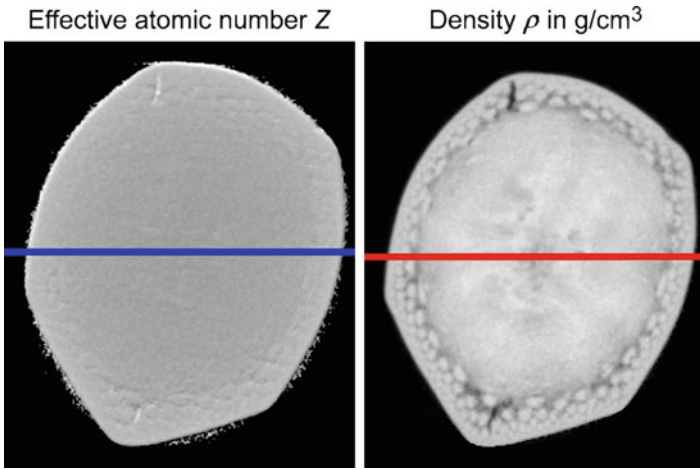


Fig. 3 Quantitative results from a 2X-CT measurement of a banana. Left: central slice showing Z_{eff} , right: corresponding distribution of mass density representing structural details inside the fruit

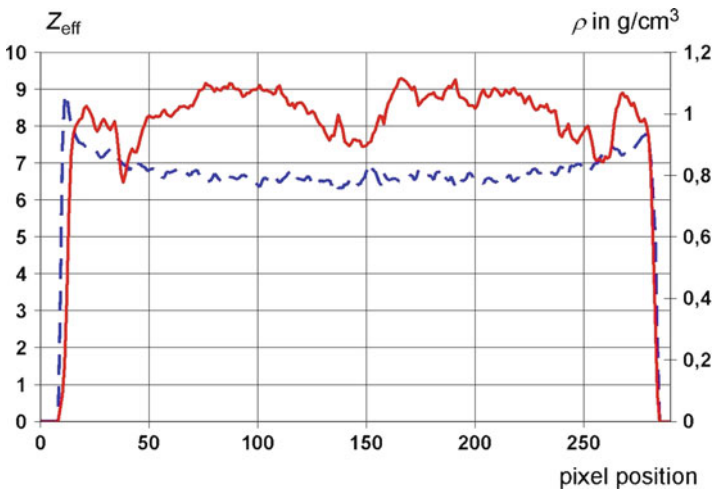


Fig. 4 Profile plots along the lines indicated in Fig. 3. Z_{eff} -values (dashed line) increase slightly towards the surface of the fruit, which is due to beam hardening. Mass density (solid line) varies strongly along the cross-section

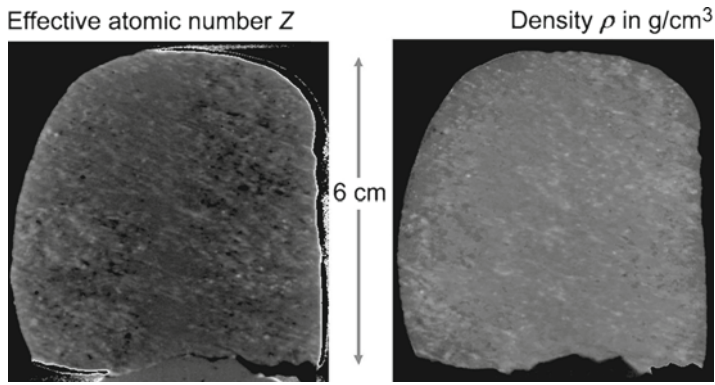


Fig. 5 Results for a Gneiss pebble. The distribution of different materials is seen in the atomic number and the density map, both generated by the 2X-CT.

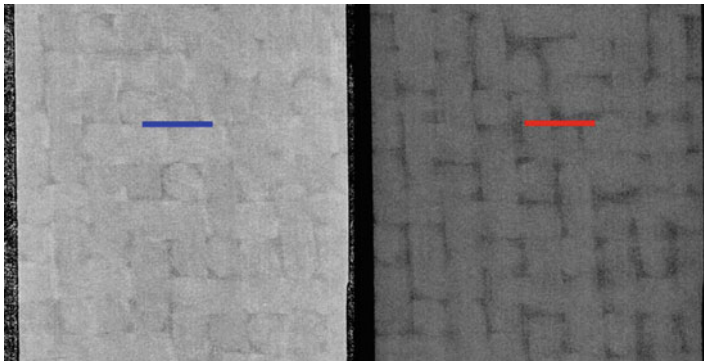


Fig. 6 2X-CT cross-sections of a CFRP sample (left: Z_{eff} , right: mass density ρ)

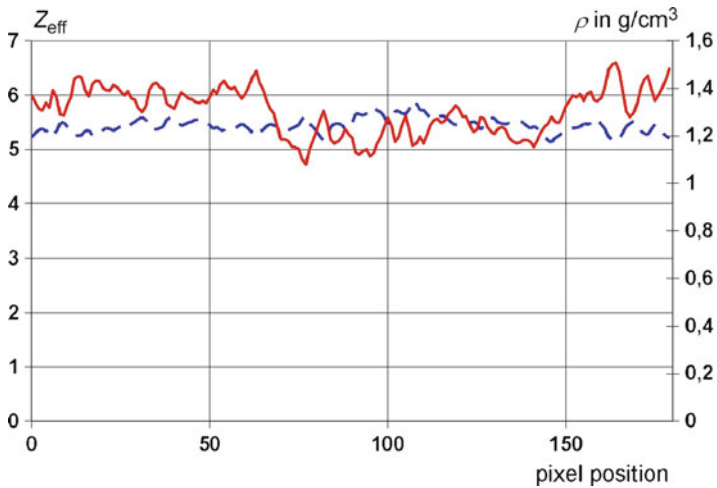


Fig. 7 Profile plots along the lines indicated in Fig. 6. Profiles correspond to the lines in the Z_{eff} -cross-section (dashed line) and mass density (solid)

Material sciences

One highly promising application of 2X-CT is the evaluation of the properties of newly developed CFRP. Fig. 6 shows the result for a CFRP sample. Data acquisition was made with 40 kV, 1 mA, 0.5 mm Al filtration for the LE-measurement and 120 kV, 0.33 mA, 0.3 mm Cu for the HE-measurement, respectively. While Z_{eff} (dashed line in Fig. 7) does not differ significantly between fiber bundles and the matrix material, the mass density changes for about 0.2 g/cm^3 .

Summary

In summary, it was shown that 2X-CT provides means for quantitative assessment of materials and objects which are of interest in industrial production, science and technology. The *2X-Suite* is an easy-to-use tool, enabling 2X-CT measurements for various fields of applications in research and industry.

References

- [1] Nachtrab F. et al. (2010), *NIM A*, DOI: 10.1016/j.nima.2010.06.154
- [2] Heismann, B.J et al. (2003), *J. Appl. Phys.* vol. 94, pp. 2073
- [3] Giersch J. et al. (2003), *NIM A* vol. 509, pp. 151 – 156