STATUS AND FUTURE ASPECTS OF X-RAY BACKSCATTER IMAGING

W .Niemann
Philips Industrial X-Ray GmbH
Röntgenstrasse 24
D-22335 Hamburg, Germany

S. Zahorodny
Philips Industrial X-Ray GmbH
5110 McGinnis Ferry Road
Alpharetta, GA 30202, USA

INTRODUCTION

Since the market introduction of the commercial system ComScan 160 [1] X-ray backscatter imaging has become an established inspection technique in certain areas of non-destructive testing, e.g. corrosion inspection on aircrafts. Several preceding publications on X-ray backscatter imaging have been focussed on the current status of the ComScan system and on topical applications [2,3,4]. In the present article the horizon shall be opened to all relevant results which have been obtained worldwide with X-ray backscatter techniques. Due to space limitations it is certainly not possible to give a complete overview, but some selected results will be reported. In reference [5] additional information and many references to this topic can be found. Furthermore, in that work reference is also given to the patent situation. Additionally to this, an overview on the history of X-ray backscatter techniques, on physical and technical foundations of the techniques and its numerous variations will be given in chapter 3.1.5 of the to-be-published handbook on NDT [6] (in German).

SELECTED RESULTS

General Remarks

The signal $I'(E')$ measured by a detector element of an X-ray backscatter system is directly proportional to a) the density of the object in the selected volume element (voxel) and b) the intensity $I(E)$ of the bremsstrahlung spectrum emitted by the X-ray tube. It will be attenuated by c) absorption of the incoming beam on its way to the voxel $\{\exp(-\mu d)\}$ and d) absorption of the scattered beam on its way to the detector $\{\exp(-\mu' d')\}$. Additionally to the signal generated by a single scatter process there is another signal which is due to e) multiple scatter (MS) inside the test object. MS is extremely important in cases of large penetration depths and/or strong absorption in the inspection object.

Review of Progress in Quantitative Nondestructive Evaluation, Vol 17
Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1998

The achievable information depth is mainly determined by d), but also by the kind of bremsstrahlung spectrum and by the MS effects. The step width and the geometrical resolution are determined by the degree of collimation of the X-ray beam L (voxel size) which is related to the scan time T per voxel by f) $T \propto L^{-7}$. In the following we will show which progress has been achieved for the items a) to f) and what has been the focus of work, respectively.

High-Precision Density Measurements

A French group from Lyon has developped a system which, by using special collimators and a 90° scatter geometry, allows the precise non-destructive determination of material density within 40 s of measurement time [7]. With the aid of calibration measurements (hydrostatic method), the backscatter apparatus has given a relative precision of 1% (0.07 absolute error) for density measurements on metallurgical powders (e.g. Distalloy AB, Fe-1.5%Cu-1.7%Ni-0.5%Mo). In contrast to previous standard methods for density measurements (hydrostatic, destructive) the new method is non-destructive and much faster (40 s instead of 20 min). It reaches almost the precision of the previous method (absolute error 0.07 instead of 0.05). There are ideas and concepts for a further increase of precision and speed for the density determination on the basis of X-ray backscattering [8,9].

High Resolution Backscatter Techniques

The commercial system ComScan 160 has been designed for the inspection of lightweight materials such as carbon fibre structures, Al etc. [1,2]. In this inspection system the X-ray beam is collimated in such a way that a resolution of 0.4 mm is achieved with the 10 mm aperture. By using a 160 kV, 19 mA X-ray tube the acquisition of 500 x 250 x 22 voxels requires a typical scan time of a few minutes for the whole inspection volume. This means that for every individual voxel a measurement time of only 1 to 3 ms is used. The typical information depth is 10 mm; the maximum selectable aperture allows a 50 mm depth.

The fact that the scantime per voxel T is related to the geometrical resolution L by the 7th power of 1/L, i.e. $T \propto L^{-7}$ [6] gives a natural reason for the very limited number of publications on high-resolution backscatter imaging; the required inspection time is very long. In [10] an apparatus is described which generates depth profiles (line scans) with very high resolution ; the scatter angle is slightly larger than 90°. A possible measurement accuracy of 1/1000“ is reported in [10]. Taking into account an integration time of 5 to 40 s per voxel results in a total scan time of 8 to 67 minutes per line profile.
In spite of the high degree of collimation of the X-ray beam, a precise determination of the location of layer boundaries in layered structures requires the use of additional image processing [11], such as deconvolution of the apparatus function. Due to considerable quantum noise in the data this problem is not easily solved.

Image Processing and Simulations

In the field of computer tomography, correction and reconstruction procedures are totally indispensable for the generation of layer images. Although backscatter imaging (as e.g. with ComScan 160) directly delivers threedimensional data sets and of course also layer images with no a priori need for reconstruction, image processing is getting more and more involved. The primary reason for this is that the generated layer images or line scans shall be corrected for artefacts which are either due to the backscatter system itself or due to the properties of the inspection object. To mention just a few important items : i) the conversion from oblique coordinates to rectangular coordinates, ii) the correction for absorption artefacts inside the inspection object and iii) the circumvention of limitations of the apparatus (scan area, apparatus function).

A simple procedure based on the combination of adjacent scans to a large mosaic has been used in [12]. In this way a large object could be displayed in one image despite the scan area limitations of the scanner.

A solution for the problem of absorption artefacts has been given in [13]. It is based on the fact that the attenuation in the test object due to Compton scattering is almost constant in the energy range of interest. Changes due to the photoelectric absorption are monitored by working at two different tube voltages, e.g. 160 and 100 kV, respectively. In [13] it has been shown how these artefacts can at least be strongly reduced with this dual energy technique.

The problem of determining the location of boundaries under the condition that the two involved materials show large differences in absorption behaviour and that a high degree of beam collimation is impossible due to time considerations has been tackled by using a double detector technique [14,15]. On the basis of a 160 kV X-ray tube the authors have determined the thickness of steel pipes with a maximum thickness of 8 mm to a relative precision of better than 10 %. This so-called transcatter technique is mainly aimed at corrosion inspection of pipelines.

Simulations of measured backscatter images up to the very last detail, i.e. by including the source function, the apparatus function, detector properties etc. are reported in the literature (see e.g. [16]). The inclusion of CAD data of the inspection object into the simulation of the backscatter images is suggested in [17].

A precise modelling of multiple scatter effects can only be achieved on the basis of statistical methods, e.g. Monte Carlo simulations. The paths of millions of incoming photons are simulated, and for predefined detector positions signals are recorded and evaluated. The reported Monte Carlo simulation in [18] was confined on single scatter events. Other groups (see e.g. [19]) have already included multiple scatter effects.

Backscatter Imaging at 450 kV

In general, the achievable information depth of backscatter imaging is dependent on the material composition, on the integration time per voxel, on the degree of beam collimation and on the energy spectrum and total power of the X-ray tube. Multiple scattering inside the test object is a further depth limitation due to the MS-induced contrast reduction.

The Compton-induced energy reduction for the scattered beam results is another physical depth limitation due to the higher absorption coefficient of the materials at lower energies. It should be noted that for scattering at 150 degrees the maximum scatter energy is only 101 / 170 / 260 keV for tube voltages of 160 / 450 / 5000 keV, respectively.

Experiments with a laboratory prototype have been performed at Philips IXR, Hamburg on the basis of a 450 kV X-ray tube with 1 to 2 cm beam diameter and a NaJ detector. The analysis of line profiles obtained parallel to the surface at a source-to-detector distance of approx. 1 m has shown the following results :

- The achievable information depth for light materials is approx. 200 mm.
- The detector system must be operated at a dynamic range of 10^3 to 10^4.
- At the larger depths multiple scattering is the dominant scatter process.
- Absorption artefacts must be corrected for.
- In the depth range 150 to 200 mm the reduction of tube voltage from 450 to 225 kV results in a signal reduction by approximately a factor of 10.

In figure 1 a comparison of line scans obtained at 450 kV (top) and 225 kV (bottom) ís shown for a scan depth of 170 mm in a sand structure. Two cavities (structures A and B) and a strong absorber (structure C) are identifiable.

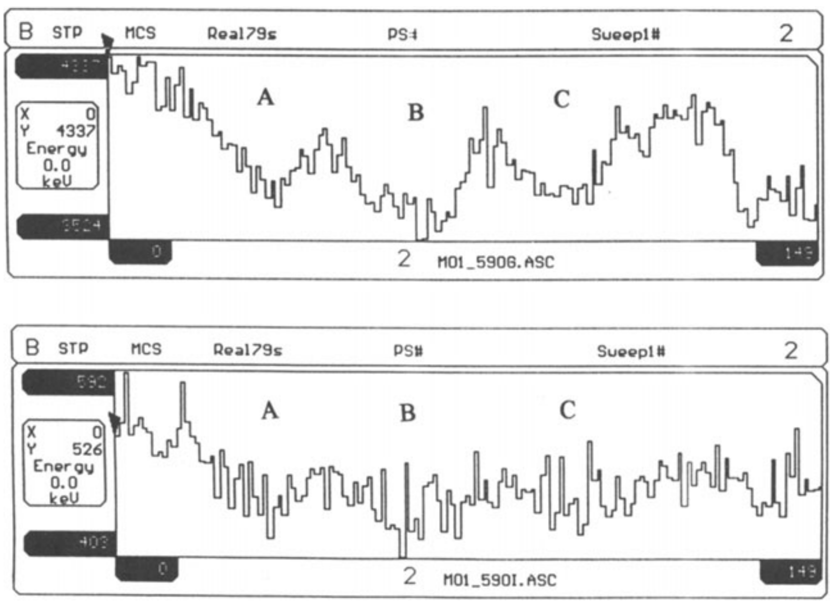

Figure 1 . Comparison of line scans at 450 kV (top) and 225 kV (bottom) at 170 mm depth in a sand structure which includes two cavities (structures A and B) and a strong absorber (structure C).

Although a significant signal from depths beyond 200 mm is registered, it is almost totally due to multiple scatter effects. We have confirmed these observations with Monte Carlo simulations [19] which are based on the EGS4 code. In figure 2 the simulated total signal and the multiple scatter contribution for a scatter volume at 100 mm depth are displayed. It can easily be seen that already at these depths multiple scattering delivers a strong contribution to the total signal.

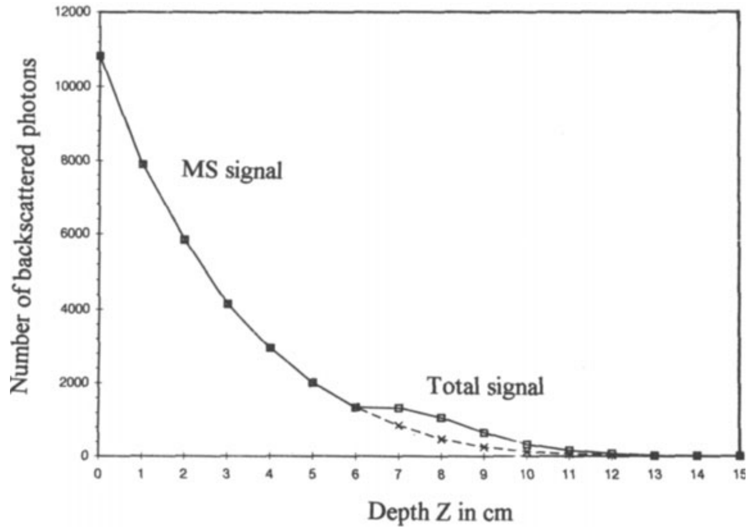

Figure 2 . Monte-Carlo simulation of multiple scattering effects in sand at 100 mm depth (energy range 100 to 250 keV, 75 Mill. photons).

REDESIGN OF THE COMSCAN 160 SCANNER

Philips IXR has redesigned the commercial ComScan 160 scanner to a new ComScan 160 II on the basis of new customer requirements and technological progress (see figure 3 and [20]). The novel design features are :

a) The scintillators in the scanner head are mounted in a tilted position now in order ro reduce the crosstalk between adjacent crystals and to increase the effective absorption length of the incoming X-rays. The smaller crosstalk results in slightly better geometrical resolution, especially for the deeper layers.
b) The signal processing has been changed from PMT current measurement to photon counting. Thus noise is reduced and contrasts are enhanced. The observed 'white dots' of the old system have totally vanished.
c) Apertures are single-pieced now to enable faster change of apertures and to avoid change by mistake.
d) The electronic rack is very compact now, and all connections are plug-in connections. This enhances the system mobility.
e) The computer system is based on an industrial PC with OS/2 multi-task operating system.
f) The data format has been changed to .TIF. This easily enables the use of ComScan data in other environments.
g) A 17"-monitor is used for system operation as well as for display of images. For display, 1 or 4 layers can be shown simultaneously.
h) During scan acquisition the displayed layer(s) can be changed (browsed) to ensure fast visual inspection results.
i) The scan data are saved on a CD-writer.

Summing up, a higher image quality and a higher mobility have been achieved with the redesigned ComScan system. Furthermore, and this is even more important for the user, throughput of the inspection system has been raised from approx. 50 scans per 8h-shift to approx. 80 scans. The time basis for this comparison is the total time needed for data acquisition, visual defect recognition and data saving. With the new system better inspection results are expected e.g. for corrosion inspection on aircrafts and sonar domes [12] and for crack inspection in ceramics [21].

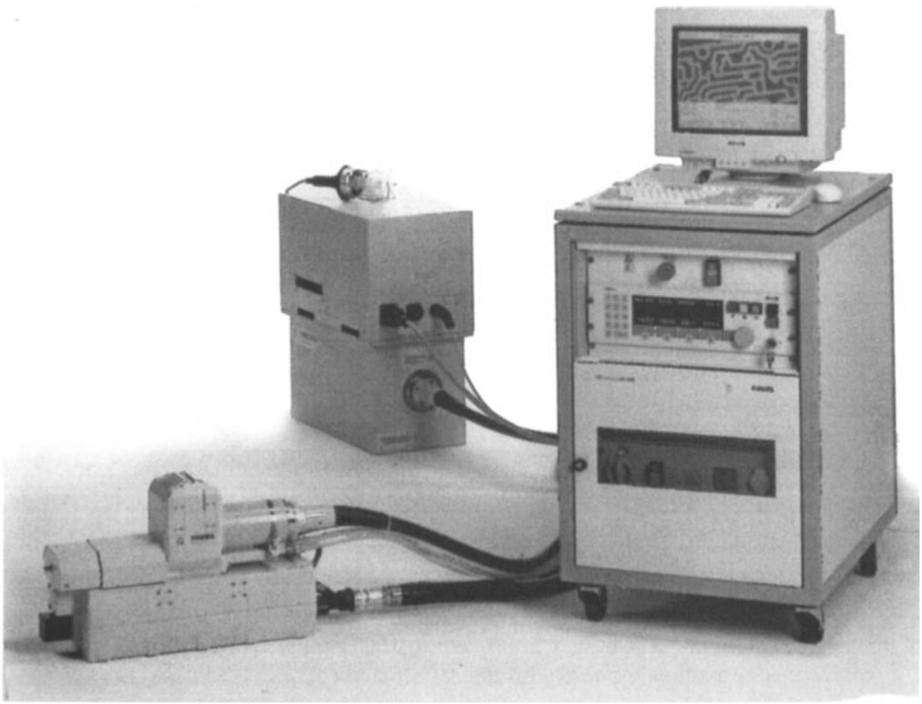

Figure 3 . The redesigned commercial backscatter system ComScan 160 II.

OUTLOOK

Keeping in mind the fascinating results e.g. on high-precision density measurements, on large penetration depths at 450 kV and the redesign of the ComScan 160 system one immediately comes to the conclusion that the backscatter techniques have a high potential for innovations, and that in the near future many more interesting and important results will appear. Especially in the field of image processing and image reconstruction where difficult tasks have to be worked on, we expect to see many new results.

REFERENCES

1. J.-M. Kosanetzky et al.: *Compton backscatter tomography of low atomic number materials with the ComScan system*. Philips Techn. Information Bulletin (1988)
2. W.Niemann : *Tomography with scattered X-rays* (in German). DGZfP Berichtsband 22, 5-14 (1991)
3. W.Niemann and W.Roye : *New applications of the Compton backscatter technique 'ComScan' in the field of archeology and monument preservation* (in German). DGZfP Berichtsband 37, 157-164 (1993)
4. W.Roye, W.Niemann and K.-H.Fischer : *The X-ray backscatter tomography ComScan*. DGZfP Berichtsband 44, 136-139 (1994)
5. B.I.Kapranov et al. : *Compton backscattering tomography: state of the art and prospects (Review)*. Russian Journal of Nondestructive Testing 30, 751-766 (1994)
6. G.Harding and W.Niemann : X-ray backscatter techniques (in German). Chap. 3.1.5 of the new German NDT handbook (to be published).
7. P.Zhu et al.: *In-line density measurement system using X-ray Compton scattering*. NDT&E International 28, 3-7 (1995)
8. J.Muller et al.: *Quantitative nondestructive evaluation of density of green state compressed products*. Nondestructive Characterization of Materials VI, Eds. R.E.Green et al., Plenum Press, New York, S.175-182 (1994)
9. P.Zhu et al.: *X-ray Compton backscattering techniques for process tomography : imaging and characterizaton of materials*. Meas.Sci.Technol. 7, 281-286 (1996)
10. L.Lawson : *Compton X-ray backscatter depth profilometry for aircraft corrosion inspection*. Materials Evaluation 8, 936-941 (1995)
11. L.Lawson and N.Kim : *Deconvolution and detectability in Compton backscatter profilometry*. Review of Progress in QNDE Vol.13, Eds. D.O.Thompson and D.E.Chimenti, Plenum Press, New York , S.1971-1978 (1994)
12. E.C.Greenawald, Y.S.Ham and C.F.Poranski : *Application of backscatter tomography* . DGZfP Berichtsband 44, 354-361 (1994)
13. G.Harding and R.Tischler, *Dual-energy Compton scatter tomography*. Phys. Med. Biol. 31, 477-489 (1986)
14. P.S.Ong et al.: *Transcatter X-ray technique for the inspection of insulated, oil-carrying pipelines*. Review of Progress in QNDE Vol.12, Eds. D.O.Thompson and D.E.Chimenti, Plenum Press, New York , S.295-301 (1993)
15. P.S.Ong et al.: *A novel X-ray technique for inspection of steel pipes*. Journal of Nondestructive Evaluation 13, 165-173 (1994)
16. V.A.Gorshkov et al.: *Reconstruction of images measured in backscattering geometry*. DGZfP Berichtsband 44, 140-147 (1994)
17. J.Gray, T.Aljundi and A.Turnbull : *Optimizing Compton backscattering parameters using a simulation code*. Review of Progress in QNDE Vol.14, Eds. D.O.Thompson and D.E.Chimenti, Plenum Press, New York , S.369-376 (1995)
18. Y.S.Ham, C.F.Poranski, and E.C.Greenawald*: Monte Carlo simulation of X-ray back-scatter tomography using visual methods*. DGZfP Berichtsband 44, 346-353 (1994)
19. G.Harding : *Inelastic photon scattering : effects and applications in biomedical science and industry*. Radiation Physics and Chemistry 50, No.1 (1997)
20. *ComScan 160 II Compton X-Ray Backscatter Inspection System*. Data sheet Philips Industrial X-Ray GmbH, Hamburg (1996).
21. M.Maisl et al., *Non-destructive testing of ceramics, composites and PCB by X-ray tomographic methods*. DGZfP Berichtsband 44, 226-233 (1994)