PLANAR AND VOLUME TOMOGRAPHY IMAGING FOR NDE APPLICATIONS

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ABSTRACT

Electronic imaging devices for gamma and x-ray based Radiography Testing (RT) have shown a remarkable presence during the last decade, due to their technical adaptability to existing inspection systems and easy availability of different configurations to suit a variety of applications. The process of NonDestructive Testing or Examination (NDT or NDE) determines the existence of flaws, discontinuities, leaks, contamination, thermal anomalies or imperfections in materials, components or assemblies, without impairing the integrity or function of the inspected component. NDE is also utilized for real-time monitoring during manufacturing, inspection of assemblies for tolerances, alignment and periodic in-service monitoring of flaw/damage growth, in order to determine the maintenance requirements and to assure the reliability and continued safe operation of a particular part. Today, one can find both analog and digital imaging systems like tube-type fluoroscopy devices, solid-state Linear Detector Arrays (LDA) and two-dimensional detector arrays like Flat Panel Detectors (FPD). These devices can be adapted to suit a variety of imaging requirements like Digital Radiography (DR) operating in online and/or real-time mode and the fast emerging Industrial Computed Tomography (ICT) imaging for non-medical applications. A typical DR and ICT system may be very compact and modular for low-energy applications. However, dedicated DR/ICT systems designed and developed for specific requirements and making use of high-energy X-rays, may be a fixed installation. The Isotope Applications Division (IAD) at BARC, Mumbai has been active in the research and development activities, in the field of advanced radiation-based imaging, for industrial applications for almost a decade. IAD has demonstrated long-back, indigenous efforts in x-ray and gamma ray-based tomographic imaging systems, for various applications. It has continued its effort to modify and develop a facility for Digital Industrial Radiography (DIR) and Volume Computed Tomography (VCT) imaging systems primarily for industrial and other non-medical applications. The present paper briefly discusses research and development efforts in the planar and volume tomography imaging for NDE applications. It may be stressed here, that the work carried out so far, was primarily aimed at indigenous technology and know-how development for various applications.
Introduction

Conventional Industrial Radiography is an adaptation of the principle of latent image formation on photographic medium, by gamma rays or X-rays for non-medical applications. The conventional gamma ray and x-ray based radiography for examination of industrial specimens has been in practice for decades and it has become an indispensable tool for industrial quality control in production, maintenance and in-service inspection. Most of the applications using film-based Radiography Testing (RT) are now standardized. Though film-based RT offers probably the best spatial resolution limited by the emulsion property, there are sometimes disadvantages associated with this method, like lack of possibility of having real-time and online inspection and maximum throughput. In terms of cost-to-benefit analysis also, though film based RT may offer a simpler option in terms of initial investment, the recurring cost on consumables may be prohibitive in the long run.

The industrial applications of tomography are still picking up primarily because, one set of specifications does not cater to all problem areas. As a result, it appears that it is difficult to build a universal ICT system and standardize it. There is in general, no concern of radiation exposure to the specimen under scanning, which is in sharp contrast to the stringent regulations for medical tomography systems. In addition to this, a broad class of industrial specimens do not have any inherent motion. Some of these fundamental differences in requirements as compared to systems for medical applications provide more freedom in specifying operating parameters. Computed tomography as such, is a complex mathematical procedure involving a number of parameters.

Fig. 1: Schematic diagram of a typical radiography and tomography setup
Slight variations in the characteristics of different sub-systems, may give rise to unique problems and necessitate a thorough study. It may also need a careful solution. The fundamental difference between ICT and conventional radiography is shown in Fig. 1. In conventional radiography, information on the slice plane designated as P1, projects into a single line, L-L; whereas with the corresponding tomographic image, full spatial information is preserved. CT information is derived from a large number of systematic observations at different viewing angles and an image matrix is then numerically reconstructed. Thus by using ICT, one can, in effect, slice open the system capabilities, that may exist. Moreover, by stacking and comparing adjacent tomographic slices of a test article, a three-dimensional image of the test article can be constructed. A fundamental task of CT systems, is to make an extremely large number of highly accurate measurements of gamma ray or X-ray transmission, through an object in a precisely controlled geometry.

The three important scanning geometries mainly from the point of view of industrial applications are as follows:

1. Parallel-beam geometry is technically the simplest and the easiest one, to understand the principles of tomography imaging. Multiple measurements of X-ray or gamma transmission are obtained, using a single highly collimated gamma ray or X-ray pencil beam and a detector. The beam is translated in a linear motion to obtain a projection profile. Scan times can be reduced with the use of a narrow fan beam of gamma rays or X-rays and a linear detector array. A translate-rotate scanning motion may be employed with a large rotational increment, which results in shorter scan times. The reconstruction algorithms are slightly more complicated than those for parallel-beam geometry, because they must handle narrow fan beam projection data.

2. A fan beam consisting generally of X-rays, illuminates a large number of detector elements arranged along an arc (equiangular) or a line (collinear). The object is fully covered by the fan beam. In general, an object rotation by 360° and no translation motion is used, to generate projection data. As a result, these rotate-only motions acquire projection data for a single image. The object can have either start-stop motion or continuous motion. There is some variation in reconstruction techniques based on different scanning mechanisms for reduced angular views.

3. A natural extension of this geometry, is to employ a two-dimensional array detector and a cone-beam of radiation such that, multiple projection lines can be acquired simultaneously and volume reconstruction can be carried out. Among various other modalities used for acquiring direct two-dimensional projections, the use of an amorphous-silicon (aSi) based Flat Panel Detector (FPD) array is common now. The FPD device can be used for direct digital radiography as well as volume tomography in an industrial imaging system.

Scintillators used in imaging applications including computed tomography can be broadly divided into two groups (a) single crystals and (b) ceramics. Single crystal scintillator such as NaI(Tl), CsI(Tl), CdWO₄ and Bi₄Ge₃O₁₂ are normally used in discrete detector configurations. The powder preparation/sintering route for the rare-earth ceramic scintillator provides high process yields, uniform scintillator quality and low cost scintillators such as gadolinium oxy-sulphide (GOS), a translucent ceramic scintillator. It is a matter of choice in terms of light output, decay time and high density for medical tomography and low-energy industrial digital radiography and tomography imaging applications.
LDA-based 2D Planar Imaging System

The use of a Linear Detector Array (LDA) in X-ray computed tomography imaging is well established. Generally, the system using an LDA, operates in a fan-beam configuration. In a non-medical tomography setup, the X-ray source and detectors are stationary and the object is rotated for scanning. In general, equi-spaced angular projections over a complete 360° object rotation are required for tomography image reconstruction, using standard Convolution Back Projection (CBP) algorithm as applied to the fan-beam scanning geometry.

In non-medical imaging applications, transmission gamma or X-rays-based computed tomography, is often regarded as a supplementary Non-Destructive Testing (NDT) tool to conventional radiography. With the availability of low cost linear detector arrays and constant potential X-ray equipments, a tomographic imaging system can be developed in a cost-effective manner for experimental purpose, provided the associated problems are taken care of. The experimental ICT system for NDT applications, a block diagram of which is shown in Fig. 2, has been developed by making use of an independent scintillator-based linear detector array, commonly used for on-line radiography of low-density specimens. The specific areas which demand special attention in the development of an experimental tomographic imaging system are (a) system alignment, (b) motion instability and (c) artifacts arising due to scattering and polychromatic nature of the Bremsstrahlung X-rays. An artifact can be thought of as an artificial defect showing up in an image and which does not represent an existing flaw in the specimen. Tomography artifacts manifest themselves in somewhat different ways, since in this imaging modality, the initial measured data is subjected to a complex mathematical treatment. Third-generation tomography systems normally use a rotate-only scan geometry, with a complete view being collected by the detector array, during each sampling interval. Since all elements of a third-generation detector array contribute to each view, rotate-only scanners impose much more stringent requirements on detector performance than do second-generation units, where each view is generated by a single detector. A single detector element of a linear detector array in a rotate-only tomographic system, records transmission data corresponding to one particular ray at one particular position in the fan-beam, through a complete rotation. Therefore, all information on a circle in the reconstructed image around the center is given by one detector element. A defective or badly calibrated detector element on the sensing device will give rise to what is called ring artifacts. The term ‘defective detector element’ is used in a broader sense and it may indicate a dead pixel element, either an element with a different response characteristics from the rest ones or a badly calibrated element. The correction methods, which can be applied to counter the effects of such elements, depend on different factors. It is seen that if the response of majority of elements of the array is unpredictable, the correction method may be difficult to arrive at. In addition to this, when a tomography system is developed out of the available detector systems and mechanical manipulators as well as associated instrumentation, it is quite possible that a lack of synchronization among various sub-systems shows up in different artifacts in the reconstructed image. It has also been observed, that a lack of synchronization between mechanical scanning mechanism and data acquisition of a computed tomography imaging system, results in artifacts in reconstructed images. These two issues have been investigated by us in the laboratory and suitable correction methods were developed for minimization of prominent artifacts in case of planar tomography imaging using LDA. The method for correcting transmission data matrix, based on the principle of minimum of difference signal, has been tried in case of the experimental system in the laboratory. The set of multiple one dimensional transmission data profiles at different angular positions are used in the correction algorithm, to find out near-360° projection in a continuous rotate-only industrial CT scanning geometry. The first 1-D profile recorded is treated as the 0° position data and remaining profiles
The experimental tomographic imaging system, which was developed in the laboratory, is briefly described below. The system consists of an X-ray source though a perfectly monochromatic radiation source would be the best choice, an Xscan0.8-410 linear array detector, a computerized scanning mechanism and related instrumentation, including both hardware and software.

A section of the three-axis mechanical manipulator including the rotary mechanism, trigger component and the detector array, which is exposed to the radiation beam are seen in the photograph (Fig. 3). A 160 kV/10mA constant potential X-ray generating system with specified effective focal spots of 1.5 (large focal spot) and 0.4 (small focal spot) as per IEC 336 was used in the experiment. These are equivalent to 1.5 mm and 0.4 mm in conventional designation. The X-ray tube (MXR-160/0.4-1.5) is manufactured by M/s. Comet AG, Switzerland. The HV generator and the control unit are from M/s. Gulmay Ltd., England. The small focal spot was selected, as it was smaller than the detector resolution. The anode voltage can be set in steps of 1 kV and the tube current can be set in steps of 0.1 mA. The finer increment values of kV and mA were helpful in optimizing the detector array. X-rays coming out of the tungsten target undergo inherent filtration in the 0.8 ± 0.1mm beryllium (Be) window of the tube. The specified radiation coverage is 40°. The high voltage unit of the constant potential X-ray generator specified short-term voltage and current stability of 0.05% / hr of set the values. The tomography system required around 10-20 seconds per scan and it was assumed that the X-ray output remained stable during this short period.

Figs. 4 (a & b) show the typical graphical user interface of the reconstruction and data pre-processing routines. The profiles (Fig. 5) of the linear detector array response to varying tube currents at a fixed anode voltage can be set in steps of 1 kV and the tube current can be set in steps of 0.1 mA. The finer increment values of kV and mA were helpful in optimizing the detector array. X-rays coming out of the tungsten target undergo inherent filtration in the 0.8 ± 0.1mm beryllium (Be) window of the tube. The specified radiation coverage is 40°. The high voltage unit of the constant potential X-ray generator specified short-term voltage and current stability of 0.05% / hr of set the values. The tomography system required around 10-20 seconds per scan and it was assumed that the X-ray output remained stable during this short period.

Figs. 4 (a & b) show the typical graphical user interface of the reconstruction and data pre-processing routines. The profiles (Fig. 5) of the linear detector array response to varying tube currents at a fixed anode voltage of the X-ray system show spatially invariant abnormal behaviour of the detector pixels. The data pre-processing algorithm developed has been found...
Table 1: Linear detector array specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Type of the detector system</td>
<td>GOS Scintillator-based linear diode array</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>512</td>
</tr>
<tr>
<td>Detector pixels used</td>
<td>260</td>
</tr>
<tr>
<td>Pixel size</td>
<td>0.8 mm(H) x 0.6 mm (W)</td>
</tr>
<tr>
<td>Detector pitch</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>Length of active area</td>
<td>410 mm</td>
</tr>
<tr>
<td>ADC resolution</td>
<td>12 bits</td>
</tr>
<tr>
<td>Control signal (PC to module)</td>
<td>via RS 232 interface</td>
</tr>
<tr>
<td>Data transfer (Module to PC)</td>
<td>via RS 422 interface</td>
</tr>
<tr>
<td>Onboard offset and gain calibration</td>
<td>Yes</td>
</tr>
<tr>
<td>External Trigger</td>
<td>Optical trigger sensor (reflecting type)</td>
</tr>
</tbody>
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The use of such a system is a cost-effective option in place of closed loop servo-drive based manipulators. The horizontal axis is parallel to the detector length and as such it is used for beam alignment. The vertical axis is used to select scanning planes and to move the object vertically in computed radiographic scanning mode. The rotary axis provides the specimen platform to hold the object and rotate. The source to detector distance \((S_D)\) is 1120 mm and source to centre-of-rotation distance \((S_0)\) is set to be 920 mm. This configuration provided a geometric magnification of 1.22. In the experiment described here, only a portion of the full length of the linear array was used such that, 260 detector elements arranged symmetrically around the central ray, fully covered the circle of reconstruction. This arrangement gave a fan beam angle of approximately 10°. This was done so that the active detector pixels receive a relatively uniform X-ray flux.

To minimize image artifacts due to such detector response in a variety of test specimens.

A three-axis PC-based stepper motor controlled mechanical manipulator was used for object manipulation and system alignment. The rotary axis provides the specimen platform to hold the object and rotate. The source to detector distance \((S_D)\) is 1120 mm and source to centre-of-rotation distance \((S_0)\) is set to be 920 mm. This configuration provided a geometric magnification of 1.22. In the experiment described here, only a portion of the full length of the linear array was used such that, 260 detector elements arranged symmetrically around the central ray, fully covered the circle of reconstruction. This arrangement gave a fan beam angle of approximately 10°. This was done so that the active detector pixels receive a relatively uniform X-ray flux.
Combined digital radiographic and computed tomographic imaging of a test specimen

The result of digital radiographic and tomographic imaging of a typical industrial test specimen is presented here. The experiment was carried out in order to visualize the internal cross-sectional details, which would be rather difficult to see by projection method (radiography) only.

Fig. 6 shows a photograph of the specimen used in the experiment for visualizing combined digital projection radiographic and computed tomographic images. A section of twelve aluminium circular tubes welded together were housed in a thin commercial metallic container with a seam-welded joint along its length. The maximum material thickness in the beam path was found to produce projection radiographic views with sufficient contrast to visualize the aluminium structure inside the container. The digital data obtained from the linear detector array was processed to obtain the typical radiographic image.

Fig. 7: (a) Radiographic view of the container assembly and (b) Radiographic view of the same specimen partially filled with water at 100 kV.
Development work has continued on an integrated digital radiography and volume (direct three-dimensional) imaging system, using a constant potential X-ray equipment (which can operate up to 420 kV of accelerating voltage) and an amorphous silicon-based Flat Panel Detector (FPD) assembly as its key components. Various sub-systems of the facility have recently been integrated and only some initial results have been obtained so far. The front-end software components have been developed in our

Fig. 8: Typical tomographic images of the container-assembly cross-sections marked (a) A₁ in Fig. 7(a) and (b) A₂ in Fig. 7(b) at 100 kV.

Fig. 7a shows the radiographic image of the container assembly under two different conditions. The image clearly shows the inside details of the specimen, where the seam joins the container wall, change in thickness in the welded portion of the tubes structure as well as the smooth thickness gradient due to circular shape of the container. Fig. 7b was obtained with the container partially filled with water. This was done to increase the material thickness in the beam path up to a certain height, so that the contrast was reduced in that portion and almost no details were seen for the aluminium structure. This is due to the fact, that the energy of the X-rays is not sufficient to record details with sufficient contrast in the given configuration. The X-ray tube voltage was kept constant at 100 kV for these two images.

Fig. 8a is the computed tomographic image of a typical cross-section of the specimen in the water-filled region. This is marked as level A₁ in Fig. 7b. It can be seen that the image distinctly shows the container’s thin wall cross-section, high thickness region of the seam joint in it and the aluminium tubes’ cross-section inside the water. The uniform-density water region has some grainy noise visible which is due to the limited signal-to-noise ratio in the input signal. This image has significant details about the internals as compared to the radiographic image in Fig. 7b. Fig. 8b is another tomographic cross-section at a level marked A₂ above the water level. The tubes are significantly curved in this plane. This is evident from the aluminium cross-sections, which are not seen circular in shape. The selected plane has not been able to cross all the tubes and some only in parts. The relative contrast is able to distinguish all the details expected in the cross-section.

X-rays and FPD-based 3D Volume Imaging System

Development work has also continued on an integrated digital radiography and volume (direct three-dimensional) imaging system, using a constant potential X-ray equipment (which can operate up to 420 kV of accelerating voltage) and an amorphous silicon-based Flat Panel Detector (FPD) assembly as its key components. Various sub-systems of the facility have recently been integrated and only some initial results have been obtained so far. The front-end software components have been developed in our
laboratory, which make use of some commercial software components in the back-end. At present, performance studies on various parameters are in progress. Fig. 9 shows the schematic diagram of the complete layout. Fig. 10 shows a photographic view of the actual setup. At the extreme left in the picture is the 420kV X-ray tube head and at the far end, the

Fig. 9: Schematic diagram of the X-ray-based Direct Digital Radiography and Volume Tomography System

FPD assembly with a shielding plate is mounted on an alignment table. Fig. 11 is the outside view of the control area in the laboratory. FPD is a fast and sensitive radiation detector and it requires exposure for a few seconds only, for general imaging applications. When the system is to be used for acquisition of large number of projection data for direct 3D tomographic reconstruction, the FPD is exposed to intense X-ray radiation continuously during the scanning sequence.

Fig. 10: Photographic view of the X-ray based Direct Digital Radiography and Volume Tomography System housed inside a shielded enclosure

Fig. 11: Control area of the X-ray-based Direct Digital Radiography and Volume Tomography System
The scanning sequence involves mechanical motion of rotary systems meant for object mounting. It has been observed, that the actual exposure duration is only about 10% of the total time taken by a typical scanning sequence. Due to operational difficulties, the X-ray device cannot be switched on and off rapidly. The other way to restrict exposure to the FPD in such operating cycle, is to use a fast-response beam shutter, which operates automatically and in unison with the motion and data acquisition system. Fig. 12a shows a motorized lead shutter assembly designed and developed in the laboratory and Fig. 12b shows the assembly mounted on the X-ray head on top of a beam collimator. Fig. 13 shows software interface of the master control programme used to automate the scanning sequence and data acquisition.
Preliminary Volume Tomography Performance of the System

The FPD can provide good quality digital projection images with spatial and contrast details. The detector provides 16 bit/pixel data with 12-bit actual resolution. The active area of the detector is around 400mm x 2800mm. The programmed exposure can be accomplished for a variety of kV and mA combinations and the detector can be calibrated for dark current as well as beam uniformity, for correct radiographic exposures. The specially developed API functions by the manufacturers, have been used to customize the FPD operations in an automated way. This was required as for volume tomography operations, the reconstruction software requires a large number of two-dimensional projections. A variety of pre-processing corrections are required before tomography image reconstruction using Feldkemp algorithm. The test results shown here have been obtained using proprietary reconstruction software and 3D ICT data presentations have been achieved using IDL software.

The test specimen used for generating initial volume tomography data on the system was a domestic electric water boiler. The test object is made up of low-density plastic material and it contains metallic components such as heating element and screws etc. The actual projection data matrix is quite large (~3k x 2k pixels). Tomographic reconstruction using such a large projection data-matrix requires a very large number (>1500) of equi-angular views. This again requires a very large scanning time. It is seen that in the present configuration, the time required for a single full-matrix...
Industrial tomography may well present an example of confluence of various branches of science and engineering like radiation physics, computer science and other signal processing techniques. Tomography imaging using penetrating radiation from sealed radioisotope sources or machine-based X-rays can be applied in different ways in industrial diagnostic applications. An Industrial Process Tomography (IPT) system for fixed installation using 662 KeV gamma radiation from a sealed Cs-137 radioisotope source and multiple detectors is being designed and developed, for research applications in cold trickle bed columns, as part of a joint collaborative project under Memorandum of Understanding between BARC and an R&D laboratory of a leading petrochemical company.

Fig. 16: Representative direct digital projection images of the test specimen

Conclusion

The paper discussed development efforts in the field of planar and volume experimental tomography imaging systems for research applications in non-destructive testing and examination of industrial and other non-medical applications. Some of the advantages and configurations of industrial digital radiography and tomography imaging systems have been presented. The development work initiated under various Plan Projects was primarily aimed at technology and know-how development for different applications. The initial data generated for test scans and the reconstructed volume data using an FPD are being analyzed and it is observed, that the reconstructions show certain noise and artifacts. The optimization of various parameters like exposure time, projection resolution angular views, pre-processing of projection
data and overall scanning geometry are in progress. A partial bibliography is provided here for reference and further reading.

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References


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