Acquisition Trajectories for X-Ray Tomosynthesis Applied to Planar Samples

Markus REHAK*, Ulf HASSLER*, Randolf HANKE*

* Development Centre for X-ray technology EZRT, a common department of the Fraunhofer Institute for Integrated Circuits IIS, Dr.-Mack-Str. 81, 90762 Fürth, Germany and Nondestructive Testing IZFP, Saarbrücken, Germany

Abstract. Usage of X-ray laminography for inspection tasks in aerospace is difficult because of low contrast structures and defects. Hence using an optimized tilt angle becomes more important. This article deals with the design of new trajectory types for use in combination with tomosynthesis reconstruction and shows how these trajectories can increase reconstruction quality.

1 Introduction

X-ray laminography is a method related to computed tomography (CT). In contrast to CT in laminographic data acquisition only a very limited angular range can be used [1]. This is causing reconstruction artefacts. Laminography is in use for printed circuit board (PCB) inspection since many years. In PCB inspection object structures like ball grid arrays or solder joints, having a very high contrast with respect to the background, are to be tested [2,3]. Therefore such reconstruction artefacts have only minor influence on automated inspection results. The state of the art reconstruction method in PCB inspection is X-ray tomosynthesis, because it combines good reconstruction quality with high reconstruction speed [1].

In composite materials the contrast of internal structures is much less and in contrast to PCB inspection the primary aim is to achieve high depth resolution and reconstruction quality by using many projections. Therefore the angular range has major influence on the reconstruction quality. While selecting a suboptimal angular range in automated PCB inspection won’t lead to problems, the interpretation of composite structures will be complicated. Therefore investigation of the angular range is necessary for achieving the best reconstruction quality.

The following chapters firstly deal with the influence of the selected angular range on the reconstruction results. Secondly it is shown how reconstruction quality can be improved by means of proper angular range selection. Finally tomosynthesis is compared to a specific algebraic reconstruction technique (ART).

2 Laminographic data acquisition and tomosynthesis

In laminography specimen and detector are moving on parallel planes. Typically both source and detector are moved on a circular trajectory in such a way, that the object is irradiated under a constant tilt angle $\varphi$ [1]. In our case object and detector are moved instead (fig 1). Laminography is suitable for large flat specimens, whose flat side is aligned in parallel to the circular trajectory. Hence the object can be very close to the source...
without causing a collision during movement. If the detector is far away at the same time a very high object resolution can be achieved.

Fig. 1: The laminography acquisition scheme: object and detector move on parallel planes. Only structures having the focus object distance are projected onto the same position on the detector during detector movement.

One reconstruction method for laminography is digital tomosynthesis [1]. It is not an exact reconstruction algorithm like the ART but a mathematical approximation. However this type of reconstruction needs only few projections for producing a slice by slice representation quality being good enough for automated inspection. Moreover this method is very fast, which is important for inline inspection. A drawback is the superposition of structures outside the plane of interest.

3 Influence of the tilt angle on the reconstruction results

As mentioned before, laminography is using a very limited angular range, which is far less than 180 degree. Thus all reconstruction algorithms, not using any a priori information, will produce reconstructions having artefacts, which are specific to the limitation of the angular range. For laminography the most distracting artefact is the so called hat-shaped artefact. Its shape is dependent on the shape of the object structure and the directions the object is irradiated and therefore on the distribution of tilt angles for each object’s position. In case of a bore hole the shape forms a symmetric cone (fig 2).

Fig. 2: Longitudinal section, x-z-plane: the tomosynthesis reconstruction produces hat-shaped artefacts above and below each object structure, which decrease reconstruction quality. This section shows a bore hole (bright), which is inside composite material (dark). The rectangle marks the true position of the bore.

Hence the selected tilt angle has certain effects on the hat-shaped artefacts:

- The height of the artefact increases with lower tilt angles. Therefore the loss of image
quality due to artefacts is higher, if a low tilt angle is selected.

- The shapes of the artefacts are dependent on the distribution of tilt angles. Each position on the detector except the centre position has its own distribution of tilt angles and each of these tilt angles differs from the selected tilt angle. The differences increase with increasing distance to the detector’s centre.

- The diameter of the circle the detector describes, depends on the selected tilt angle. If this diameter becomes smaller than the detector’s border length, the tilt angles near the detector boundaries are not distributed multidirectionally any longer (fig 3). Any unidirectional distribution stands for another lack of information and accordingly more reconstruction artefacts.

- The z-range of the reconstructible area is influenced by the tilt angle. Using digital tomosynthesis as reconstruction method, the regions above and below the focus slice both form a pyramid. While the size of the focus slice is independent on the tilt angle the size of all other slices decreases with increasing tilt angle (fig 4). If due to this reason a test region cannot be visualized using a single acquisition, an overlap region for each acquisition has to be defined. Thus using a higher tilt angle can lead to a higher amount of required acquisitions and therefore higher overall data acquisition time.

Fig. 3: Normally each position inside the object is irradiated multidirectionally (left side). But if the tilt angle becomes too low with respect to the detector size, some positions could be irradiated only unidirectionally (right side). This causes a lack of information and accordingly more reconstruction artefacts.

Fig. 4: The reconstructible z-range depends on the selected tilt angle. The z-range for the right geometry is smaller than for the left geometry, because the used tilt angle is higher on the right side.
4 Test object and acquisition parameters

The test object is a plate of carbon fibre composite material, 240.0 mm by 140.0 mm in size and 12.5 mm in thickness, including a set of bores, each 3.0 mm in diameter and of known depth (fig 5), and including some glass fibres. A possible inspection task for this object is the detection of the bore depth.

Due to mechanical reasons the used CT system was only able to realize a laminographic data acquisition using a tilt angle of not more than eleven degree. Therefore the object also was simulated using Scorpius XLab™. This step additionally had the advantage to explore the effects on hat-shaped artefacts, caused by changing the tilt angle, without the influence of other physical effects like scatter radiation or noise.

The CT system was equipped with the following devices:

- X-ray source: Feinfokus FXE-225.99
- X-ray detector: Perkin Elmer XRD-1621, 2048 x 2048 pixels, 200 µm pixel size

Both the real acquisition and the simulation were made using the following acquisition parameters:

- Source voltage: 110 kV
- Source current: 150 µA
- 10 times averaging of each projection
- Exposure time: 1 s per projection
- Focus object distance: 167 mm
- Focus detector distance: 810 mm
- Resulting magnification factor: 4.85

For proving the comparability of simulation and real measurement the object was both measured by using the CT system above and simulated by using Scorpius XLab™ with equal X-ray parameters and a tilt angle of eleven degree. Figure 6 shows a x-z-plane through the bores and the comparability of simulation and real measurement.
Fig. 6: Longitudinal cut through the bores (x-z-plane). Top: reconstruction of real acquisition. Middle: reconstruction of simulation. Bottom: the grey value profile through the bores illustrates the comparability of simulation and real measurement.

5 Influence of the tilt angle on the reconstruction quality

5.1 Low tilt angle compared to high tilt angle, circular trajectory

For showing the influence of the tilt angle on the reconstruction quality, data acquisition was simulated using two circular trajectories with 10 and 40 degree tilt angle. Figure 7 shows a slice at a depth of 1.1 mm below surface. The reconstructed slice of the 10 degree trajectory offers a better contrast than the slice of the 40 degree trajectory. Furthermore the slice of the 40 degree trajectory shows some bright fog like artefacts along the bores, which decrease contrast furthermore. In other words, 10 degree tilt angle seems to be better.

Fig. 7: Comparison of a simulated slice containing all bores, using different tilt angles (x-y-plane). Top: 10 degree tilt angle and very good contrast. The outer bores are in a region of unidirectional tilt angle distribution. Middle: 40 degree tilt angle and comparatively worse contrast, but more uniform representation of the bores. The bores are encircled by fog like artefacts which decreases sharpness. The reconstructible region is smaller. The profile diagram shows, that the bores are blurred in case of a high tilt angle.
Figure 8 shows a slice at a depth of 3.7 mm below surface, containing only a couple of bores. In this case the slice quality of the 10 degree trajectory in contrast to the 40 degree trajectory is decreased by very strong hat-shaped artefacts because the presence of these artefacts increases with decreasing tilt angle (fig 8).

These effects can be illustrated much better using a longitudinal cut through the bores (fig 9). In case of 10 degree tilt angle the hat-shaped artefacts are so strong, that any automated detection is much harder than in case of 40 degree tilt angle, even if the contrast is less here.

Hence the selection of a specific tilt angle has assets and drawbacks. The logic approach is the combination of both reconstructions. Just the reconstructible area is dependent only on the 40 degree tilt angle data set. This is discussed in the next section.

5.2 Combination of tilt angles for blurring hat-shaped artefacts

The idea is that a combination of more than one tilt angle during a single data acquisition could improve reconstruction quality by smoothing the hat-shaped artefacts. Of course there is no chance, that all negative effects in tomosynthesis can be removed completely. Hence the artefact will still be visible, but if it would be possible to blur them more, contrast and sharpness of true objects may be increased.

As mentioned in chapter 3, the shape of an artefact is dependent on the distribution of tilt angles. If for instance a bore is in the centre, where the tilt angle is constant, and only a constant tilt angle is used, the resulting symmetric cone hat-shaped artefact is shown with very high contrast. Let’s assume, a couple of reconstructions are available, each acquired...
using a different circular trajectory. All other acquisition parameters remain unchanged. In this case the bore can be found at exact the same position in every reconstruction as well as the hat-shaped artefacts, but each artefact has another shape. A reconstruction using all different tilt angles will lead to a bore still having a very high contrast, but the hat-shaped artefacts lose influence due to homogeneous smearing of artefact structures.

To verify this, a simplified version of the test object containing only the centre bore was simulated in Scorpius XLab™. It is important to always use the same number of projections, because the signal to noise ratio increases with the number of projections. Therefore the following trajectories, each having 140 projections, were simulated (fig 10):

- Twice a circular trajectory with 10 and 40 degree tilt angle. These trajectories serve as starting basis.
- A trajectory consisting of two concentric circles combining 10 and 40 degree tilt angle. Both circles contain 70 projections in this case.
- A trajectory consisting of seven concentric circles combining 10 to 40 degree tilt angles in steps of 5 degree. In this case each circle contains 20 projections.
- A circular trajectory with 25 degree tilt angle to compete against the concentric circular trajectories, because 25 degree is the mean value of 10 and 40 degree.
- A spiral trajectory consisting of seven turns. The inner tilt angle is 10 degree, the outer tilt angle 40 degree. In this case we have 140 different tilt angles in steps of 0.22 degree.

![Visualized trajectories](image)

As expected hat-shaped artefacts shrink with increasing tilt angle while object sharpness is decreased. The ring structure beyond the cone is still visible with decreased thickness and contrast (fig 11). If 10 degree is combined with 40 degree tilt angle, the hat-shaped artefact is still visible very clearly, but with less contrast. By means of combination of seven different tilt angles, the artefact becomes highly blurred, while the bore itself gets a clean shape more and more. The logical case is a spiral trajectory combining 140 different tilt angles. The resulting profile is very close to the theoretical rectangular profile.

It also has to be proved, whether a circular trajectory with 25 degree tilt angle could yield an equivalent result. In fact the corresponding grey value profile in figure 10 is also very close to the ideal rectangular profile. But a smoothing of the hat-shaped artefacts cannot be found here. Hence a combination of many different tilt angles is much better.
Fig. 11: Longitudinal cuts through a single bore and the corresponding gray value profiles. The profile is expected to match a rectangular shape. a) 10 degree circular trajectory. b) 40 degree circular trajectory. c) Two concentric circles trajectory 10 and 40 degree. d) Seven concentric circles trajectory 10 to 40 degree in steps of 5 degree. e) Spiral trajectory 10 to 40 degree and 7 turns. f) 25 degree circular trajectory. With increasing number of different angles the hat-shaped artefacts are smoothed more and more. At the same time the shape of the profile is converging to the ideal rectangular shape. The diagram below shows the deviation of grey values out- and inside the bore for all trajectories. Lower values are better.

6 Tomosynthesis compared to ART

Finally tomosynthesis was compared to a specific ART, which doesn’t use any a priori information. Figure 15 shows, that ART reconstructed data of the specimen, shown in figure 5, shows artefact structures very similar to tomosynthesis data. Just the appearance is different, because the voxels reconstructed by tomosynthesis are not a measure for the density of the object.
Therefore using more than one tilt angle during data acquisition should increase both, ART and tomosynthesis reconstruction quality similarly. For proving this, the trajectory consisting of seven concentric circles from section 5.2 was reconstructed using ART (fig 16). The hat-shaped artefacts are smoothed as well.

Fig. 16: Circular trajectory compared to a multi circular trajectory. Left: Circular path with a tilt angle of 25 degree. Right: Trajectory of seven concentric circles, tilt angles from 10 to 40 degree in steps of 5 degree. The hat-shaped artefacts are smoothed.

7 Summary

Summing up the strong influence of the tilt angle and the shape of the acquisition trajectory on reconstruction quality has given the following results:

- Circular trajectories with a very low tilt angle cause strong hat-shaped artefacts.
- Circular trajectories with a very high tilt angle cause only small hat-shaped artefacts, but image contrast and sharpness is worse.
- By using many different tilt angles hat-shaped artefacts can be smoothed while image sharpness and contrast can be improved in both tomosynthesis and ART.

Therefore the trajectory should contain many different tilt angles. The range of tilt angles should contain very low tilt angles and very high tilt angles as well.

References

