Investigation of the application of phase contrast imaging using a point X-ray source to industrial non-destructive testing

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X-Tek Systems, a division of Nikon Metrology UK, designs, develops and manufactures microfocus X-ray radiography and computed tomography systems for industrial non-destructive testing. The range of X-ray acceleration voltages of its current standard products is 130–450 kV. It is widely known that X-ray images can be created using phase contrast formed by the natural propagation of X-rays. Simulation of the natural propagation of X-rays through a cylindrical test sample predicted a small contrast peak at the boundary between the cylinder material and air. Comparison data were obtained using an X-ray source with acceleration voltage above 100 kV. The simulation results correlated well with the experimental data. A further practical example (a ‘magic mirror’ amulet from an old Japanese shrine) is introduced and discussed. In this specimen, we detected intensity variation including the effect of phase contrast in the operating region above 100 kV. In summary, natural propagation phase contrast was observed in radiographic images from a standard point X-ray source with acceleration voltages exceeding 100 kV.

1. Introduction

X-Tek Systems was started in the founder’s garage in 1986 and moved to Tring, Hertfordshire, in the early 1990s. Metris acquired X-Tek Systems in 2007 and Nikon subsequently acquired Metris in 2009 and formed Nikon Metrology with its Head Office in Leuven, Belgium. X-Tek Systems has developed and manufactures an extensive range of microfocus...
X-ray radiography and computed tomography (CT) systems for industrial non-destructive testing (NDT). The range of electron acceleration voltages available from a point X-ray source (as standard products) is currently 130–450 kV.

Roger Hadland (founder of X-Tek Systems) and Nick Hadland (his son) obtained a high-contrast image of a house fly in 1989 (figure 1) using a point X-ray source operating at 60 kV (tungsten reflection target, 100 µA). The estimated size of the focal spot was 10 µm (full width at half-maximum, FWHM). This was an unexpected encounter with phase contrast imaging, although they did not know of the existence of phase contrast at that time. This image illustrates the exquisite detail that may be captured in specimens that are radiographically ‘soft’, where the absorption contrast might be expected to be low.

This has led to our interest in the production of phase contrast images formed by natural propagation using point X-ray sources of over 100 kV acceleration voltage.

2. Theory and application to X-ray tool

The principle of phase contrast was well explained mathematically by Teague [1] in 1985 using the intensity transport equation, although his numerical analysis was done with a wavelength of 1.0 µm.

Remarkable results in the X-ray region were reported by Wilkins et al. [2] in 1996. Their images of a goldfish’s fin are now world famous.

A detailed theoretical study of X-ray natural propagation was reported by Pogany et al. [3] in 1997 employing the Fresnel–Kirchhoff integral. According to this paper, in the case of plane waves and a one-dimensional object (where the x-direction is perpendicular to the propagation direction and x = 0 represents the centre of the object), the intensity I(x) is given by the following equation for large x:

\[
I(x) \approx 1 + \frac{\lambda z}{2\pi} \phi''(x). \tag{2.1}
\]

Here \( \lambda \), \( z \) and \( \phi''(x) \) are the wavelength, detecting position and the second derivative of the phase function, respectively. This indicates that the phase contrast intensity is proportional to the second derivative of the phase function, so a polychromatic X-ray spectrum can still provide phase contrast.

In the case of products supplied by X-Tek, we need to consider a part of a spherical wave from effectively a point X-ray source. The polychromatic X-ray spectrum consists of bremsstrahlung and fluorescent X-rays from the target. There are practical size limitations to the X-ray tool, which constrain the maximum separation between an object and its radiographic image on the detector,
hence limiting magnification. The pixel size of the detector is also an important factor for the phase contrast signal.

Now let $R_1$, $R_2$ and $P$ represent the distance from the X-ray source to the object, the distance from the object to the detector and the pixel size of the detector, respectively (figure 2). Spherical wavefront 1 is deformed to wavefront 2 by the object due to its absorption and its phase function. Then, the following equations are derived:

$$R_1 + R_2 = L$$  \hspace{1cm} (2.2)

and

$$M = 1 + \frac{R_2}{R_1}.$$  \hspace{1cm} (2.3)

Here, $L$ and $M$ represent the distance from the X-ray source to the detector and the magnification of the projected image on the detector, respectively. The closest phase contrast peak $D_m$ on the detector, caused by the material at the centre of the object, is obtained at the phase term in the Fourier transformation of the Fresnel–Kirchhoff integral equal to $\pi/2$; $x_m$ is the scaled value on the object plane. Then

$$x_m = \left(\frac{2\lambda R_2}{M}\right)^{1/2}$$  \hspace{1cm} (2.4)

and

$$D_m = M x_m.$$  \hspace{1cm} (2.5)

In order to detect the phase contrast ideally, the pixel size of the detector should be limited as follows:

$$P < D_m.$$  \hspace{1cm} (2.6)

Now adopting $\lambda = 1.24 \times 10^{-5} \text{ (\mu m)}$ (100 kV) and fixing $L = 1000 \text{ (mm)}$, $D_m$ is calculated for four pairs of values $(R_1, R_2)$; these cases are shown in table 1.

The data in table 1 suggest that a detector with pixel size smaller than 50 $\mu$m and a high magnification are to be preferred in order to observe good phase contrast in the image. In fact, the X-ray source, although very small, does have finite size, and this is magnified by $R_2 / R_1$ times on the detector plane. This smears the phase contrast signal. Ideally, the source size on the detector should be smaller than the pixel size.
Figure 3. X-ray spectrum (tungsten transmission target at 160 kV). (Online version in colour.)

Table 1. Case study of tool parameters (100 kV).

<table>
<thead>
<tr>
<th></th>
<th>$R_1$ (mm)</th>
<th>$R_2$ (mm)</th>
<th>$M$</th>
<th>$x_m$ ($\mu$m)</th>
<th>$D_m$ ($\mu$m)</th>
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<tr>
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<td>500</td>
<td>500</td>
<td>2</td>
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<tr>
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<td>10</td>
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<tr>
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<td>50</td>
<td>950</td>
<td>20</td>
<td>1.09</td>
<td>21.7</td>
</tr>
<tr>
<td>case 4</td>
<td>10</td>
<td>990</td>
<td>100</td>
<td>0.495</td>
<td>49.5</td>
</tr>
</tbody>
</table>

3. Simulation and experimental result

Simulation of the natural propagation phase contrast X-ray spectrum was performed using proprietary software developed in house by Nikon. The X-ray spectrum was calculated by SpekCalc [4]. A tungsten transmission target on a beryllium window and an acceleration voltage of 160 kV were used for this calculation. The spectrum obtained is shown in figure 3. The average X-ray energy is approximately 100 kV, which was used for table 1.

A Gaussian brightness distribution (FWHM = 3 $\mu$m) in the source plane is assumed. An aluminium cylinder with a radius of 2.5 mm was adopted as a specimen object. The simulation was performed with a magnification $M = 14$. Figure 4 shows a simulation result of the whole signal intensity variation on the detector with 75 $\mu$m pixel size. This is the same as the pixel size of the detector that we used in the following experiment. A small peak can be observed at both edges. The phase contrast intensity measured by the detector is smeared from that of the original wavefront by its quantization filtering. Decreasing the pixel size from 75 to 1 $\mu$m causes the peak of the phase contrast signal to increase from 1.05 to 1.27.

Experimental data were obtained from an aluminium cylinder (2.5 mm radius). An X-ray source with tungsten transmission target, 160 kV beam voltage and source size less than 2 $\mu$m (FWHM) was used. $R_1$ and $R_2$ were 52 mm and 678 mm, respectively, with 14 $\times$ magnification. A Dexela 1512 CMOS detector with pixel size of 74.8 $\mu$m was used to produce the image. Figure 5a shows a radiographic image of the aluminium cylinder that we obtained. Figure 5b shows the X-ray intensity distribution integrated along the cylinder (at the left edge). A small amount of
simulated phase contrast signal for an aluminium cylinder (2.5 mm radius), 14× magnification, Gaussian source FWHM = 1 µm, 160 kV tungsten transmission target, 75 µm pixel size detector. (Online version in colour.)

signal enhancement can be seen at both edges of the cylinder. This is qualitatively consistent with the simulation result as shown in figure 4.

4. Example of non-destructive testing

The ‘magic mirror’ has been manufactured in Japan from the seventeenth century as a kind of concealed technology. These objects have religious significance. China may have a longer history of making similar artefacts. The principle of the ‘magic mirror’ is that very subtle and shallow concave and convex variations of the mirror surface create a specific image from the reflection of light in a specific direction. The specific image is formed only for plane parallel incident light such as the light from the Sun. This phenomenon can be understood as a phase contrast image in the visible light region. There is, or was, a hidden structure on the back side of the mirror. The surface on the front conforms to this hidden structure so as to create the convex and concave variations on the mirror front surface. We are interested in the radiographic image of this ‘magic mirror’.

An amulet, used as a talisman for the safety of travellers, which includes a ‘magic mirror’, was obtained at the old shrine Tsurugaoka Hachimangu (founded in AD 1191) in Kamakura, Japan (this is illustrated in figure 6). The silver-coloured mirror (21 mm diameter) adheres to the gold-coloured etched metal plate (40 × 65 mm). The Chinese characters on the left-hand side signify the name of the shrine, Tsurugaoka Hachimangu, and those on the right-hand side mean the amulet is for use as a travel talisman. On the surface of the ‘magic mirror’, there seem to be vague concave and convex structures when viewed from certain directions under room illumination. Defined structure cannot be found even by using an optical microscope. When this ‘magic mirror’ is irradiated by sunlight, the reflected light forms a clear image of two doves. This image is a symbol representative of this particular shrine.

In order to investigate the hidden structure on the rear side of the mirror, an X-ray source with a tungsten transmission target (where the maximum acceleration voltage and the source size are 160 kV and 2 µm (FWHM), respectively) was used. The setting parameters of $R_1$ and $R_2$ were approximately 76 mm and 707 mm, respectively, with 10.3× magnification. The acceleration voltage of 125 kV was adopted in order to extract the data from the etched plate effectively by
setting an intensity threshold. A Varian PaxScan 4030 amorphous silicon detector with pixel size of 127 μm was used. Figure 7 shows an X-ray radiographic image of the ‘magic mirror’ part. Surprisingly, a very clear image of two doves was obtained. The width of the white line defining the outline of the doves was measured as 40–50 μm on the object by reference to the diameter of the mirror.

There are two possibilities for the origin of this white line. One possibility is less absorption by the rear side groove; the other possibility is phase contrast caused by the rear side structure.

Figure 5. (a) Radiographic image of aluminium cylinder (2.5 mm radius), 14 × magnification, 160 kV tungsten transmission target, 74.8 μm pixel size (Dexela CMOS). (b) X-ray intensity distribution integrated along the cylinder (at the left edge in figure 5a), 14 × magnification. (Online version in colour.)
5. Discussion

According to equations (2.1) and (2.4), longer wavelengths (smaller X-ray photon energy) are more suitable for the production of phase contrast images. Contrary to the conventional wisdom, we tried to produce phase contrast-enhanced images using an X-ray source with an
acceleration voltage larger than 100 kV because this energy range is required in industrial NDT. We investigated metal artefacts that are not easy to penetrate with low-energy X-rays.

The simulation results indicated that this was a promising approach to obtain images with phase contrast content. However, experimental data showed only very tiny phase contrast signals or ambiguous results with mixed phase and absorption contrast. It will be necessary to use finer pixel size detectors to obtain clearer results. Further development of such detectors by suppliers is desirable.

6. Summary

Phase contrast signals resulting from natural X-ray propagation can be observed in the radiographic images from a standard point X-ray source with acceleration voltages exceeding 100 kV. These signals can very usefully supplement the absorption information and enhance image quality especially at boundaries. In order to make the phase information signals stronger, detectors with finer pixel sizes will be needed.

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References