DOI: 10.1784/insi.2008.50.3.124

Digital imaging system for linac X-rays for NDE of case bonded solid rocket motors

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Submitted 5 December 2007
Accepted 7 January 2008

Digital X-ray radiography has been found to be an appropriate NDT tool for Quality Assurance of large size solid rocket motors, high explosive charges, etc. This technique provides quick and comparable image quality as compared to conventional film radiography. A CCD-based Digital Imaging System (DIS) integrated with a 4 MeV linac X-ray source, installed for the first time in India at HEMRL, Pune, has produced promising image quality of the large size objects, which helps in detailed data analysis using dedicated image processing software. Furthermore, digital data can be obtained in a very short time and stored conveniently.

Keywords: Digital radiography, solid rocket propellant grain, non-destructive evaluation, high-energy X-rays.

Introduction

Digital radiography[1] has been increasingly used in the industries in view of faster processing, good image quality[2, 3], reduction in time, ease of image storage and retrieval etc. A number of digital detection systems such as image intensifier (IIT), computer radiography[4], flat panel[5], and CCD-based systems[6] are the potential detection systems for the low-energy X-ray source (less than 200 kV), that is generally used in the medical field as a diagnostic tool. However, a few of them such as flat panel, computer radiography, CCD-based imaging are being utilised as the detection systems for high-energy X-ray sources (more than 500 kV) but to a limited extent because of less service life expectancy, slow reduction in sensitivity and smaller imaging area. In addition, other area detectors like Silicon Intensified Target (SIT) and converter screens have also been used with high-energy sources but CCD camera-based digital imaging[7] systems are very widely chosen for high-energy X-rays because of their flexibility for choice of the imaging area and spatial resolution and more service expectancy. Although detailed information regarding the use of this digital detection system with low- as well as high-energy X-ray sources for various industrial applications is available in the literature, very limited information regarding the application of these systems in the field of high-energy materials such as solid rocket propellants or high-energy charges is available. In view of this fact, a detailed study has been carried out for first time on two different thickness solid case bonded composite propellant using a digital imaging system with 4 MeV X-ray machine to generate exhaustive data on image quality and voluminous defects.

This paper mainly describes the details about the equipment, its performance, image processing and interpretation and finally the data generation using the digital imaging system (DIS), with a view to assess the usability of the system for carrying out NDT of large size motors.

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2. Experimental

2.1 Equipment

The schematic diagram of the digital imaging system is given in Figure 1.

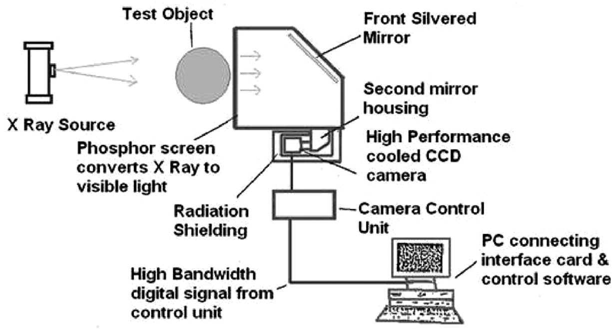

Figure 1. Schematic of digital radiography system

The Digital Imaging System (DIS) mainly consists of a phosphor screen, two front silver-coated flat mirrors, an optical lens system, a high-performance cooled CCD camera, camera control unit and a personal computer with required control and image processing tool. The imaging system, as shown in Figure 2, is placed on a three-axis manipulator and integrated with the existing linac head. The system is electronically connected to the linac head for synchronised movement. The radiographic image information in terms of visible light from the screen is focused on to the CCD camera after passing through the lens system and reflection from the mirrors. The CCD camera is connected to the personal computer (PC) through a camera control unit. This unit controls the duration of exposure of the camera to the incident light and the readout of the CCD. The signal strength in CCD elements is digitised to the 16 bit levels and then used as the grey level of pixels of the digital radiographic image displayed directly on the computer screen. The duration by which the CCD chip should get charged for collection of information is decided through the control software. With the

Figure 2. Photograph of digital imaging system for high-energy X-rays

help of the same software the digital image can be processed, stored and retrieved. The phosphor screen, mirror, lens system and the CCD camera are housed in an optically shielded box.

For improvement in image quality, a secondary collimator has been fixed on the linac head. The secondary collimator has four jaws with independent movement. Each of the collimator jaws is capable of attenuating the radiation by around 95%.

The detail feature of the digital imaging system (DIS) is as follows:

Screen size	:	750 mm × 500 mm
Elements on CCD chip	:	2048 × 2048 pixels
A/D resolution of CCD	:	16 bit
Pixel size	:	13.5 μm^2
Dark current (at -50°C)	:	< 0.01 e/pix/sec
Operating temperature of CCD	:	-50°C

2.2 Materials

Two case-bonded motors with composite propellant having outer diameter of 420 mm and 1000 mm were radiographed with the digital imaging system for radiographic interpretation. Both the motors were having around 3 mm of casing thickness and 2-6 mm of insulator thickness at different locations.

2.3 Procedure

The motor was kept horizontally on a pair of roller stands between the imaging system and linac source. The motor axis was aligned in such a way that it was perpendicular to the X-ray beam centreline. For normal shots the beam centreline indicated by the laser beam was allowed to pass through the axis of the motor. From the control room the X-ray beam was switched ON and allowed to stabilise for a constant dose rate. The CCD was then exposed with the help of the control software from the control computer for the required time of exposure, which depends on the dose rate, FFD (film-to-focus distance), film-to-object distance etc. For better image quality, the collimator was adjusted for radiography of the region of interest. The radiographic images were taken with different FFD, object-to-film distance, exposure time and collimation for each motor for initial parameter optimisation.

The radiographic image quality was assessed with the help of step-hole type Perspex IQI (Image Quality Indicator) fixed on the source side of motor surface. The IQI was fixed at the maximum thickness position with the help of grease. The radiographic image interpretation was carried out after assessing the image generated by various image processing tools available with the in-built software.

3. Results and discussion

3.1 System performance

The system is verified for the image quality initially with a standard line pair image pattern fitted in place of the conversion screen. The f-stop was adjusted to minimise the vignetting effect with optimum duration of exposure as shown in Figure 3.

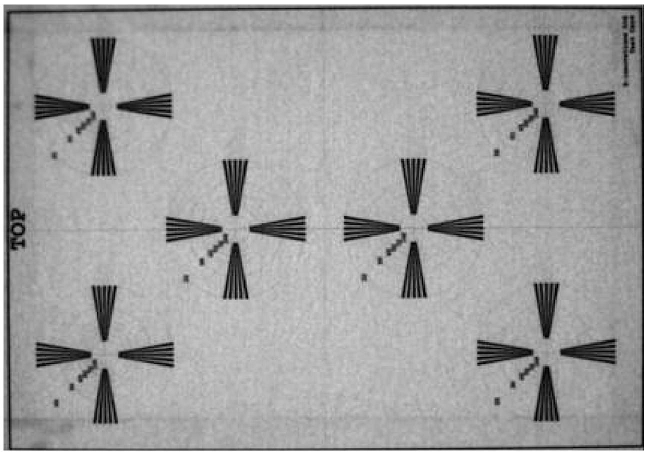

Figure 3. Image of test pattern

As shown in Figure 4, the CCD has a linear response with time for a particular radiation dose rate. Figure 5 shows the linear variation of the grey level to the dose received at the screen. This graph corresponds to the linear variation of grey levels with dose input, which is in contrast with non-linear characteristics of optical film density film with input dose. These Figures also show that without any radiation dose, the system has minimum grey level that indicates the dark image generated by the system.

3.2 Radiography of rocket motors

3.2.1 Effect of parameters on image quality

It has been observed that, unlike the case of film radiography, the image quality is better if there is an optimum distance maintained between the object and the detector plane. The exposure time of the CCD usually follows the trend of exposure time for film radiography in terms of reduction in exposure time. As the time of exposure increases, information on more regions is captured by the radiographic image for interpretation because of the cylindrical geometry of the object. It is observed that beyond certain exposure there is saturation in the image. Unlike film radiography, it is also found that if a region is exposed for a longer duration than saturation, the other nearby regions also get saturated which results in loss of information. The exposure time for the thickest portion of the 420 mm-diameter motor is optimised to be 100 s, whereas for 1000 mm diameter motor it is 320 s. For radiography of the same region by film radiography, it takes 5 and 20 min respectively, so there is a drastic reduction in time of exposure. It is clearly observed that, by using the collimator for tangential shots, the image quality improves, whereas for normal shots use of the collimator does not make much difference to image quality.

3.2.2 Analysis of radiographs of motor having diameter 420 mm

Figure 6 shows two radiographs of the 420 mm-diameter case-bonded motor. Figure 6(a) shows the feature of change in the

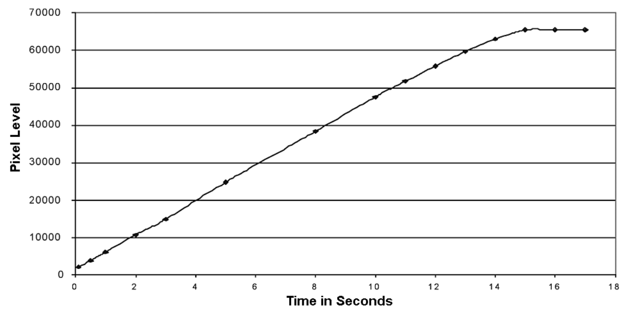

Figure 4. Linear variation of grey level with time of exposure for different dose rate

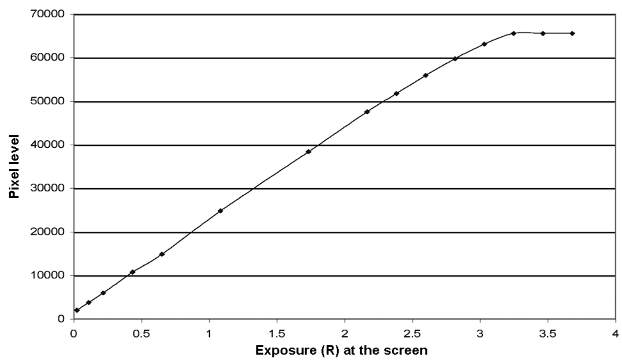

Figure 5. Pixel level *vs* exposure received at the imaging plane

geometry of port of the motor. It clearly shows the external features present on the motor casing as well as the welding present on the casing. Figure 6(b) shows the two voids detected in the propellant, having depths of 10 mm and 5 mm. The vertical white bar shown in the image is due to the harness ring. After proper image processing, the void detected in the image is more clearly seen (Figure 6(c)). Because of the larger imaging area and more dynamic range, the information about the propellant as well as the interfaces is captured in one single shot and all information is seen by changing the image processing parameters, (Figure 6(b) and 6(d)). Figure 6(e) shows the film radiograph of the same region of the rocket motor, which indicates that the digital radiographic image is very much comparable with the film radiograph. The sensitivity achieved by this imaging system for this motor is about 1.2% compared to 1% for film radiography.

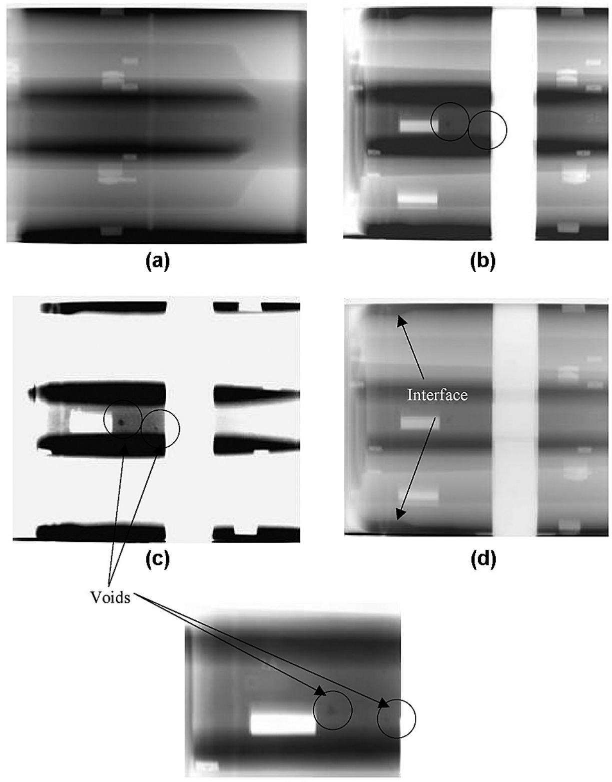

Figure 6. Digital radiograph of 420 mm-diameter rocket motor: (a) indicates the feature of changing geometry of port area, (b) shows two voids of different dimensions, (c) processed image for better clarity of voids, (d) processed image for viewing information regarding the interfaces, (e) film radiographic image of the partial region having voids

3.2.3 Analysis of radiographs of motor having diameter 1000 mm

Figure 7 shows the radiographs taken for propellant of a 1000 mm-diameter motor. Figure 7(a) shows the radiograph of the region where the propellant thickness is minimum for this motor, whereas Figure 7(b) shows the radiograph of the region having maximum propellant thickness. Figure 7(b) also shows the detected void in the propellant having a depth of 30 mm. Figure 7(c) shows the processed image for better clarity of the void. The radiography sensitivity obtained for this motor is about 1% compared to 0.8% for film radiography.

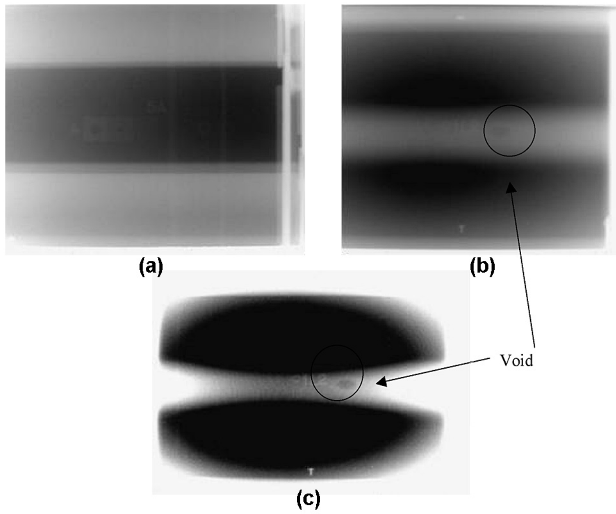

Figure 7. Digital radiograph of 1000 mm-diameter rocket motor: (a) radiograph of minimum thickness region, (b) radiograph of maximum thickness region. It also indicates the presence of void, (c) process radiograph for better visibility of void

4. Conclusion

Digital imaging system based on a CCD camera is an appropriate system for carrying out radiography of large case-bonded rocket motors (diameter 420 mm to 1000 mm) with high-energy X-rays because of large image size and reduction in exposure time. This system gives good image quality (~1.2%) relatively with less exposure time. The system has a large dynamic range and shows linearity in its total range of grey levels resulting in better coverage of the region than for film radiography. The system is a better choice for longer service life.

5. Acknowledgement

The authors are grateful to the Director, HEMRL for giving permission to publish this paper. The authors are also thankful to fellow colleagues for their support and help.

6. References

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