CPC(HEP & NP), 2011, **35**(11): 1074–1078 **Chinese Physics C** Vol. 35, No. 11, Nov., 2011

Novel correction method for X-ray beam energy fluctuation of high energy DR system with a linear detector*

YANG Min(杨民)[1;1)] CHEN Hao(陈浩)[2] MENG Fan-Yong(孟凡勇)[3] WEI Dong-Bo(魏东波)[1]

[1] School of Mechanical Engineering and Automation, Beijing Univ.
of Aeronautics and Astronautics, Beijing 100191, China
[2] Institute of Applied Electronics, China Academy of Engineering Physics, Mianyang 621900, China
[3] State Key Laboratory of Multiphase Complex Systems, Institute of Process Engineering,
Chinese Academy of Sciences, Beijing 100190, China

Abstract: A high energy digital radiography (DR) testing system has generated diverse scientific and technological interest in the field of industrial non-destructive testing. However, due to the limitations of manufacturing technology for accelerators, an energy fluctuation of the X-ray beam exists and leads to bright and dark streak artifacts in the DR image. Here we report the utilization of a new software-based method to correct the fluctuation artifacts. The correction method is performed using a high pass filtering operation to extract the high frequency information that reflects the X-ray beam energy fluctuation, and then subtracting it from the original image. Our experimental results show that this method is able to rule out the artifacts effectively and is readily implemented on a practical scanning system.

Key words: X-ray testing, accelerator, X–ray beam energy fluctuation, high pass filter, artifacts

PACS: 87.59.B- **DOI:** 10.1088/1674-1137/35/11/018

1 Introduction

Utilization of a high energy X-ray digital radiography system is of importance to test objects with a high density and large size [1–4] in the industrial non-destructive testing field, due to the advantages of its high dose ratio and strong penetration capability. To generate this kind of high energy X-ray, it is necessary to use an accelerator such as a cyclotron, an induction linear accelerator, an RF linear accelerator, or an electron linear accelerator. Basically, the energy stability of the X-ray beam is one of the most important factors to estimate the quality of the accelerators [5–7]. Taking the electron linear accelerators with high energy pulsed power as an example (these are widely used in high energy X-ray DR scanning systems) the instability of the accelerator system gives rise to the energy fluctuation of the X-ray beam and eventually leads to the bright and dark streak artifacts in the DR image. Fig. 1 shows the high energy X-ray DR scanning system with an accelerator and a linear detector. The fan X-ray beam generated by the accelerator penetrates the object and finally arrives at the linear detector. The accelerator and the linear detector are installed on different pillars, placed opposite each other. Together, the accelerator and the detector are able to move vertically along their own pillar to make a full scan of the object. The linear detector receives the X-ray photons penetrating through the object and converts them to digital signals to produce the DR image. During the movement of the accelerator and the detector it is inevitable that a random energy fluctuation of the X-ray beam is generated due to the limitation of the manufacturing technology for the accelerator. The sensitive linear detector is able to detect any subtle fluctuations and generate the bright and dark streak artifacts on the output DR image. The detected energy fluctuation

---

Received 27 January 2011, Revised 21 March 2011

* Supported by National Natural Science Foundation of China (60872080, 61077011), National State Key Laboratory of Multiphase Complex Systems (MPCS-2011-D-03) and Beijing Municipal Commission of Education (BMCE) under the Joint-Building Project

1) E-mail: minyang.ndt@263.net

of the X-ray beam is caused by the hardware used, rather than the tested object itself. Thus, we can understand that the fluctuation is a kind of system error. Fig. 2 shows the DR image with bright and dark streak artifacts, which resulted in an incorrect recognition of the DR image. Recent improvements in the quality of the accelerator system have been demonstrated to be effective in controlling the energy fluctuation of the X-ray beam to less than 1% [8], due to the increasingly rapid development of the power semiconductor technology and especially the emergence of the solid-state high-voltage pulse modulator based on solid-state switch technology. Obvious bright and dark streak artifacts in the DR image are, however, still detectable, as a result of the amplification of a subtle energy fluctuation of the X-ray beam by the linear detector with a high dynamic range and high sensitivity used in the DR scanning systems. Related correction methods for the energy fluctuation of the X-ray beam mainly focus on upgrading the hardware and the accelerator structure design [9–11], which are either actually difficult to implement in a certain duration or raise the cost of the hardware significantly. In this study, we constructed a software-based method to correct the energy fluctuation of the X-ray beam. The artifacts were corrected and the quality of the DR image was improved effectively.

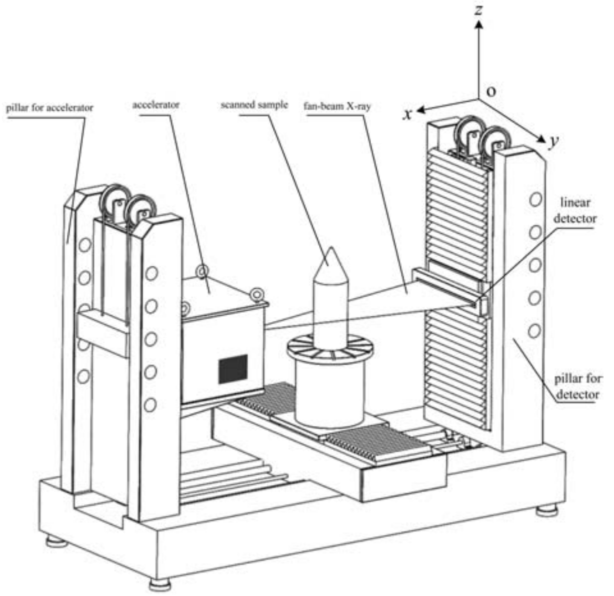

Fig. 1. The high-energy X-ray DR scanning system with linear detector.

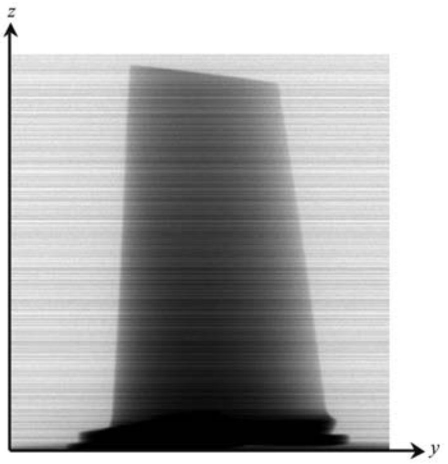

Fig. 2. The DR image with bright and dark streak artifacts.

2 Correction method

By analyzing the scanning process, we found that the signals of the bright and dark streak artifacts in the original DR image are normally in the high frequency domain. Here we define the original DR image as $p'(y,z)$, we can divide the DR image into three parts:

$$p'(y,z)=p(y,z)+E(y,z)+n(y,z) \tag{1}$$

where $p(y,z)$ is the ideal DR image without any artifacts and noise; $E(y,z)$ is the fluctuation information of the X-ray beam energy received by the detector, i.e., the bright and dark streak artifacts; and $n(y,z)$ is the random noise. If averaging the original DR image $p'(y,z)$ along the row direction (Y direction in Fig. 2), we can get a column data expressed as:

$$\begin{aligned}\bar{p}'(z) &= \frac{1}{M}\sum_{y=1}^{M}p(y,z)+\frac{1}{M}\sum_{y=1}^{M}E(y,z)\\ &\quad +\frac{1}{M}\sum_{y=1}^{M}n(y,z)=\bar{p}(z)+\bar{E}(z)+\bar{n}(z),\end{aligned} \tag{2}$$

where M is the total number of the detector units. Obviously, the averaged column data $\bar{p}'(z)$ are smoother than before. They contain three parts: $\bar{p}(z)$, $\bar{E}(z)$, and $\bar{n}(z)$. $\bar{p}(z)$ is the column data of the ideal DR image averaged along the row direction, which can be considered as the low frequency information in most cases; $\bar{E}(z)$ is the fluctuation information of the X-ray beam energy averaged along the row direction, which can be considered as the high frequency information; $\bar{n}(z)$ is the column data of the 2-D random noise data averaged along the row direction that tends to a constant, and can be considered as low frequency information.

Based on the above analysis, we propose a high pass filtering method to extract the high frequency information out of $\bar{p}'(z)$, so as to minimize the possibility of the system error. Fig. 3 shows the flow chart of constructing this method.

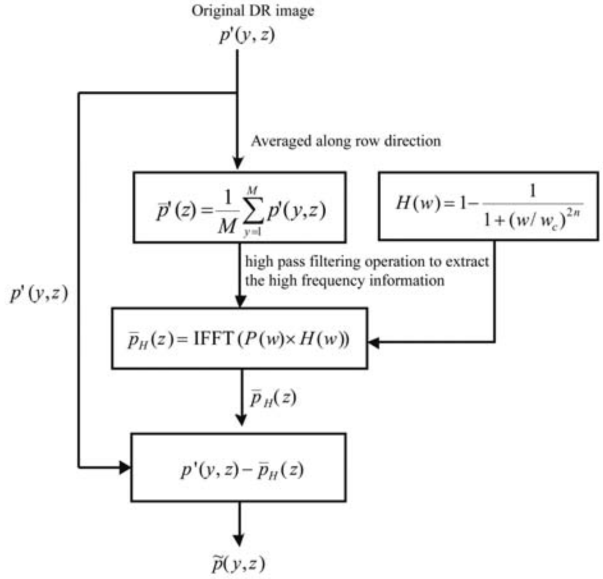

Fig. 3. Flow chart of the correction method.

Here we define the high frequency information as $\bar{p}_{\mathrm{H}}(z)$. One can readily understand that $\bar{p}_{\mathrm{H}}(z)$ reflects the fluctuation information of the X-ray beam energy. Therefore, we use $\bar{p}_{\mathrm{H}}(z)$ as a good estimate of $\bar{E}(z)$, and apply the Butterworth high pass filter to extract $\bar{p}_{\mathrm{H}}(z)$ [12]. Eq. (3) shows the frequency expression of this filter:

$$H(w)=1-\frac{1}{1+(w/w_{\mathrm{c}})^{2n}}, \tag{3}$$

where n is the order of the filter (n is defined between 6 and 9); w_{c} is the cut-off frequency that is close to the Nyquist frequency ω_0 when the fluctuation of the X-ray beam energy is low. For the value of ω_{c} and ω_0, we suggest the definition, $\omega_{\mathrm{c}}=0.5\sim0.8\omega_0$; $w_0=1/(2d)$, where d is the height of the detector unit. The procedure of the high pass filtering operation is shown as follows:

Step 1, conducting 1-D Fourier transform on $\bar{p}'(z)$: $P(w)=\mathrm{FFT}(\bar{p}'(z))$, and multiplying $P(w)$ by $H(w)$;

Step 2, conducting inverse Fourier transform: $\bar{p}_{\mathrm{H}}(z)=\mathrm{IFFT}(P(w)\times H(w))$;

Step 3, subtracting $\bar{p}_{\mathrm{H}}(z)$ from each column of $p'(y,z)$ to obtain the corrected image $\tilde{p}(y,z)$.

3 Experimental results

To verify the effectiveness of the method proposed above, we carried out an experiment in a 6 MeV DR scanning system. The parameters of the 6 MeV DR scanning system were: Accelerator energy: 6 MeV; focal spot size: 1.5 mm; detector unit size: 0.083 mm; distance from the focal spot to the detector: 2600 mm; number of the detector units: 2048; speed of the accelerator and the detector: 1200 mm/min; Fig. 4 (a) shows the original DR image (namely $p'(y,z)$) of the object acquired under the above conditions. The bright and dark streak artifacts caused by energy fluctuation of the X-ray beam were not neglectable. These artifacts absolutely decreased the image quality and thereby resulted in a wrong judgment of the image. According to the correction method constructed above, we acquired a column data $\bar{p}'(z)$ and the high frequency information $\bar{p}_{\mathrm{H}}(z)$, as described in Step (1)–(2), and subtracted $\bar{p}_{\mathrm{H}}(z)$ from each column of $p'(y,z)$, and finally obtained the corrected image $\tilde{p}(y,z)$ as shown in Fig. 4(b). One can clearly observe that almost no artifacts can be discerned. To support the effectiveness, we first plotted the curve of $\bar{p}'(z)$ as shown in Fig. 4(c). We can see that $\bar{p}'(z)$ contains much high frequency information, which is considered to be from the energy fluctuation of X-ray beam. We then averaged the corrected image (namely $\tilde{p}(y,z)$) along the row direction and plotted the curve of the averaged data, as shown in Fig. 4(d). In contrast, the curve of the averaged data was smoother, which strongly revealed that the correction method was able to rule out the high frequency information that reflects the energy fluctuation of the X-ray beam effectively.

By further analysis, we find that the high frequency information which is ruled out by the above correction method not only includes the X-ray beam energy fluctuation, but also includes the useful detailed information of the scanned sample with a complicated structure in some cases. By choosing appropriate values for orders and cut-off frequency of the high pass filter, a certain amount of the useful information can be preserved. So designing the high pass filter, namely choosing the values of n and ω_{c} is the key step in the correction method. In the above correction example, we set $n=6$ and $\omega_{\mathrm{c}}=0.75\omega_0$. At the same time, in order to analyze the loss of detailed information after the high pass filtering operation used quantitatively in the experiment, we calculated the entropy, the spatial frequency, and the standard deviation of the DR image. Basically, these are three key parameters to describe detailed information, such as texture features and edge details of a given image

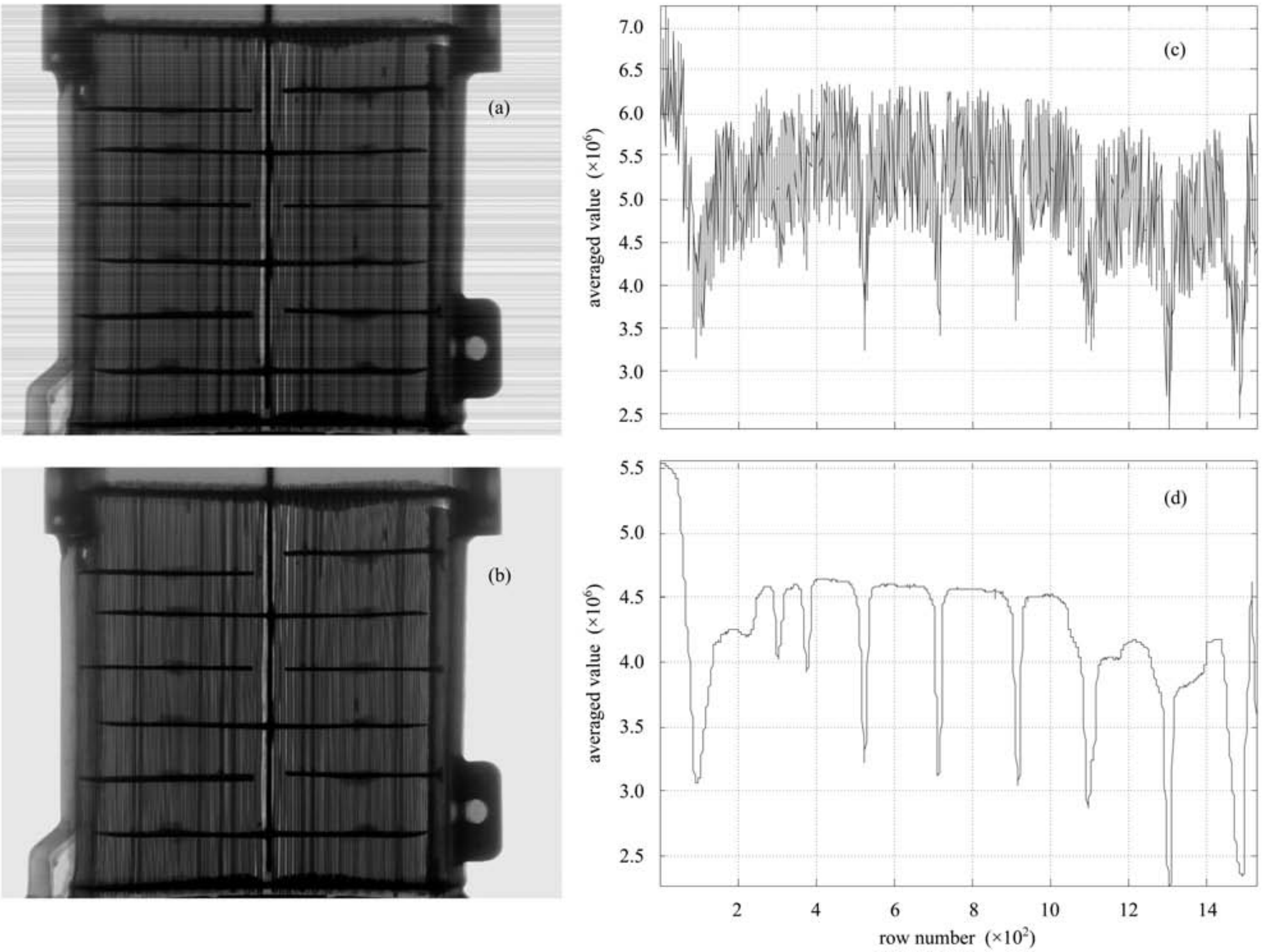

Fig. 4. Example of the energy fluctuation of X-ray beam correction. (a) The original DR image; (b) The corrected DR image; (c) The curve of $\bar{p}'(z)$; (d) The curve of the data obtained by averaging the corrected image along the row direction.

[13, 14]. In a mathematical way, their definitions are given as follows: Entropy (H):

$$H = -\sum_{i=0}^{L-1} p(i)\log_2 p(i). \tag{4}$$

Spatial frequency (SF):

$$RF = \sqrt{\frac{\sum\limits_{m=1}^{M}\sum\limits_{n=2}^{N}\left[p(m,n)-p(m,n-1)\right]^2}{M\times N}}, \tag{5}$$

$$CF = \sqrt{\frac{\sum\limits_{n=1}^{N}\sum\limits_{m=2}^{M}\left[p(m,n)-p(m-1,n)\right]^2}{M\times N}}, \tag{6}$$

$$SF = \sqrt{RF^2+CF^2}. \tag{7}$$

Standard deviation (Std):

$$Std = \sqrt{\frac{1}{M\times N}\sum_{m=1}^{M}\sum_{n=1}^{N}\left(p(m,n)-\bar{p}\right)^2}, \tag{8}$$

where $p(i) = N_i/N$, N represents the total number of pixels in the DR image, N_i represents the number of pixels whose gray value equals i. L represents the total gray level steps of the image, $p(m,\ n)$ represents the image. M and N represent the height and the width of the image, respectively. SF is the spatial frequency; RF and CF are the row frequency and the column frequency, respectively.

Table 1 compares the calculated values of H, SF, and Std before and after correction. The values were determined on the basis of the images in Fig. 4. From these results, we can see that the corrected image has reduced the values of all three parameters, that is, all the values were decreased by less than 2%. This decrease strongly suggests that through designing an ideal high pass filter, the correction method can be used to rule out the X-ray beam energy fluctuation artifacts, while preserving the useful detailed information of the original DR image.

Table 1. Quantitative comparison between the pre- and post-corrected images.

	entropy	variance	space frequency
the original DR image	17.260	89.021	21.115
the corrected DR image	16.986	87.984	20.772
the reduce percentage	1.59%	1.16%	1.62%

4 Conclusion

We have explored a new and effective method for correcting the energy fluctuation of an X-ray beam in a high energy DR scanning system. The correction method is established by first acquiring the high frequency information that reflects the X-ray energy fluctuation via a high pass filtering operation on the column data obtained by averaging the original DR image along row direction, and then subtracting the high frequency information from each column of the original data to get the final corrected image. From the above experimental results, we can summarize the following conclusions: (1) The correction method is based on the original DR image without any accessorial hardware devices and any pre-calibration of the scanning system. (2) The correction algorithm is simple and thus will be easy to implement by software. (3) The correction method can preserve the useful detailed information of the DR image effectively by choosing suitable orders and cut-off frequencies of the high pass filter. (4) The method can also be used in 2D-CT, because during the 2D-CT scanning, the energy fluctuation of an X-ray beam usually causes bright and dark streak artifacts in the projection sonogram, which are similar to the artifacts mentioned above.

References

1 HAN, Y P, HAN Y, LI, R H et al. Nucl. Instrum. Methods A 2009, **604**: 760–764

2 Atsushi F, Mitsuru U, Futaro E et al. Nucl. Instrum. Methods B., 2005, **241**: 921–925

3 Baldazzi G, Rossi M, Querzola E et al. IEEE Transactions on Nuclear Science, 1995, **42**: 575–579

4 Kanamori T. Journal of Nuclear Science and Technology 1989, **26**: 826–831

5 Asaka T, Kawashima Y, Takashima T et al. Nucl. Instrum. Methods A 2004, **516**: 249–269

6 Ziemann, Volker. Nucl. Instrum. Methods A., 2006, **556**: 45–51

7 Kato R, Isaka S, Sakaki H, Kashiwagi S et al. Nucl. Instrum. Methods A, 2004, **528**: 244–248

8 Merminga L, Bisognano J J. Energy stability in a high average power FEL. Proceedings of the 1995 Particle Accelerator Conference, 1995, **4**: 2690–2692

9 JIN K, PEI Y J, JIANG D M et al. Nucl. Instrum. Methods A, 2002, **488**: 473–477

10 Meier E, Biedron S G, LeBlanc G et al. Nucl. Instrum. Methods A, 2009, **609**: 79–88

11 YAN Tang，Hughes T P, Genoni T C. Implementation of Spread Mass Model of Ion Hose Instability in Lamda. Proceedings of the 2007 Particle Accelerator Conference, 2007. 3408–3410

12 ZHANG Ruan-Yu, LUO Xiao-Bing, LI Tai-Hua. Nuclear Science and Techniques, 2006, **17**: 232–236

13 Xydaes C, Petrovi V. Electronic Letters, 2000, **36**: 308–309

14 IELLA G. Information Fusion, 2003, **3**: 259–280