THE CHOICE METHOD OF LIGHT SOURCE RADIUS IN X-RAY PHASE CONTRAST IMAGING SYSTEM

ВЫБОР РАДИУСА ИСТОЧНИКА В ФАЗОВОКОНТРАСТНОМ МЕТОДЕ ФОРМИРОВАНИЯ РЕНТГЕНОВСКИХ ИЗОБРАЖЕНИЙ

Jie Wu

School of Medical Instrument and Food Engineering, University of Shanghai for Science and Technology, Shanghai, China

E-mail: jieusst@163.com

Based on the partially coherent optical theory, a new theoretical model is established about the X-ray light source radius of X-ray phase contrast imaging system. Through the integral phase contrast modulation transfer function, a comprehensive analysis about the light source radius is made. Then the light source radius selection methods are investigated. Finally, an actual imaging experiment is shown to confirm the choice method of light source radius in X-ray phase contrast imaging system.

Ключевые слова: *X-ray phase contrast, light source radius, micro focus.*

Поступила в редакцию 27.09.2012.

1. INTRODUCTION

From the 1990s, the X-ray phase contrast imaging technology has developed gradually, it relies on the X-ray phase shift degree, for those weak absorption material, the phase shift is often significantly greater than its absorption attenuation, even more than 1000 times higher [1, 2]. Therefore, the X-ray phase contrast imaging technology can effectively detect the internal structure of weak absorption material. This not only makes up for the weakness of traditional absorption imaging, but also extends the X-ray detection range to the weak absorption materials, and the imaging spatial resolution can reach the sub micron level [3, 4, 5].

At present, micro-focus X-ray phase contrast imaging is a research hot spot, because it has these characteristics, simple optical method, low cost, suitable for experiment and easy operation, etc. It records the Laplacian of edge details of the imaging objects, so it has broad application prospects in the clinical and laboratory research.

However, in the former published research literatures, the theoretical model basis can be divided into two categories, one is evolved directly from the hard X-ray synchrotron radiation imaging theory, the X-ray is assumed to be parallel light. Another category assumed micro-focus point to be entirely ideal coherent light with ideal spherical wave, which are reported by S. W. Wilkins, A. Pogany, A. Momos etc [4–6]. Lately, Chika Honda , A. Olivo, Xi-zeng Wu, and domestic Chen Min, Yu-hong, have introduced partial coherence theory to phase contrast imaging theoretical model analysis, but the light source radius of micro-focus has not included their theoretical model especially, and lacking of the concrete example data analysis in these literatures [7–9].

Therefore, in this paper, first of all, a new integral phase contrast modulation transfer function model is established considering of the light source radius of X-ray micro-focus , then the theoretical simulation and calculation are analyzed, after that, a micro-source selection principle and a parameter optimization method are proposed, finally, the actual imaging experiments verify the model and method.

2. Materials and methods

The micro-focus X-ray phase contrast imaging system diagram is shown in Fig. 1. X-ray is assumed to spread along the z direction, a experimental object is placed between the X-ray source and the image detector. Suppose that the light source is circular with a radius of R_0 , the distance from the light source to the object is D, the distance from the object to image detector is Z, the light source coordinate system is $x_0o_0y_0$ coordinate, the object

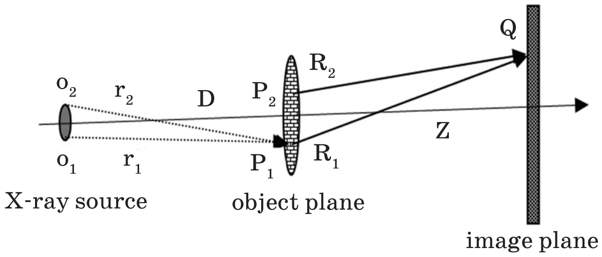

Fig. 1. Micro focus X-ray phase contrast imaging system diagram.

coordinate system is $x_1o_1y_1$ coordinate, the image detector coordinate system is xoy coordinate. To simplify the theoretical model, assume that two unrelated points o_1o_2 emits the partially coherent X-ray, the thin object is weak absorption, the light path and other symbols are shown in Fig. 1.

The coherence of any two points in light field can be described as the mutual intensity, using Van Cittert-Zernike assumption, any two points on the light source is statistical independent [10, 11], the mutual intensity is:

$$J(O_1, O_2) = I(O_1)\delta(x_{01} - x_{02}, y_{01} - y_{02}). \qquad (1)$$

In the spread process from the source to the front surface of the object, according to the mutual intensity propagation theory, the mutual coherence function at the front surface of the object can be expressed as:

$$J_0(P_1, P_2) = \frac{1}{\lambda^2} \iint_\Omega I(O_1) \frac{\exp ik(r_1 - r_2)}{r_1 r_2} dS. \qquad (2)$$

Assuming the object projection function with T, the mutual intensity after the object can be expressed as:

$$J(P_1, P_2) = T(P_1)T^*(P_2)J_0(P_1, P_2). \qquad (3)$$

After passing through the object, X-ray continues to spread and overlap in image plane, similarly, according to the mutual intensity propagation theory, get the Eq. (4) :

$$I(Q) = \frac{1}{\lambda^2} \iint_S \iint_S J(P_1, P_2) \frac{\exp ik(R_1 - R_2)}{R_1 R_2} dS_1 dS_2. \qquad (4)$$

Under the paraxial approximation, using the binomial expansion approximation:

$$R_1 \approx Z + \frac{(x - x_1)^2 + (y - y_1)^2}{2Z},$$
$$R_2 \approx Z + \frac{(x - x_2)^2 + (y - y_2)^2}{2Z}. \qquad (5)$$

Substitute the denominator of integral part in Eq. (4) by Eq. (5), the image intensity distribution can be expressed as:

$$I(x, y) = I(Q) = \frac{\exp(jkZ)}{\lambda^2 Z^2} \iint_S \iint_S J(P_1, P_2) \times$$
$$\times \exp(\frac{ik}{2Z}|(x - x_2)^2 - (x - x_1)^2 + (y - y_2)^2 - \qquad (6)$$
$$- (y - y_1)^2|)dx_1 dx_2 dy_1 dy_2.$$

For the expression convenience, the Fourier transform of plane intensity distribution is:

$$\tilde{I}(u, v) = \frac{\exp(jkZ)}{\lambda^2 Z^2} \iint_S \iint_S J(x_1, x_2; y_1, y_2) dx_1 dx_2 dy_1 dy_2 \times$$
$$\times FT\left\{\exp(\frac{ik}{2Z}|(x - x_2)^2 - (x - x_1)^2 + \right. \qquad (7)$$
$$\left. + (y - y_2)^2 - (y - y_1)^2|\right\}.$$

Simplify the Fourier transform in the Eq. 7:

$$FT\left\{\exp(\frac{i\pi}{\lambda Z}\left[(x - x_2)^2 - (x - x_1)^2\right]\right\} =$$
$$= \exp\left\{\frac{i\pi}{\lambda Z}(x_1^2 - x_2^2)\right\} FT\left\{\exp(2\pi i x \frac{x_2 - x_1}{\lambda Z}\right\} = \qquad (8)$$
$$= \lambda Z \exp\left\{\frac{i\pi}{\lambda Z}(x_1^2 - x_2^2)\right\} \delta\left[x_1 - (x_2 - \lambda Z u)\right].$$

Take Eq. (8) into Eq. (7), integral with x_1, y_1, Eq. (9) can get:

$$\tilde{I}(u, v) = \left[i\pi\lambda Z(u^2 + v^2)\right] \times$$
$$J(x_2 - \lambda Z u, x_2; y_2 - \lambda Z v, y_2) \times \qquad (9)$$
$$\times \iint \exp\left\{-i2\pi(u x_2 + v y_2)\right\} dx_2 dy_2.$$

Similarly, convert the formula 2 to the frequency domain representation, and take it into the $\int J(x_2 - \lambda Zu, x_2; y_2 - \lambda Zv, y_2)$, and get:

$$J_0(x_2 - \lambda Zu, x_2; y_2 - \lambda Zv, y_2) = \\ = \frac{1}{\lambda^2 D^2}\exp\Big[\frac{\pi}{\lambda D}(\lambda^2 D^2(u^2+v^2)2\lambda Z(x_2 u + y_2 v))\Big] \times \\ \times \iint I(O_1)\exp\Big[-i2\pi(x_{01}\frac{Z}{D}u + y_{01}\frac{Z}{D}v)\Big]dx_{01}dy_{01}. \quad (10)$$

The $S(u,v)$ indicates the Fourier transform of light intensity angular distribution:

$$S(u,v) = \iint I(O_1)\exp\big[-i2\pi(x_0 u + y_0 v)\big]dx_0 dy_0. \quad (11)$$

Therefore, the integral in Eq. (11) can be expressed as $S(\frac{Z}{D}u, \frac{Z}{D}v)$, this is the Fourier transform of the effectively light intensity distribution, so Eq. (11) can be re-written as

$$J_0(x_2 - \lambda Zu, x_2; y_2 - \lambda Zv, y_2) = \\ = \frac{1}{\lambda^2 D^2}\exp\Big[\frac{\pi}{\lambda D}(\lambda^2 D^2(u^2+v^2)2\lambda Z(x_2 u + y_2 v))\Big] \times \\ \times S(\frac{Z}{D}u, \frac{Z}{D}v). \quad (12)$$

Take Eq. (12) and Eq. (3) into Eq. (9), the Eq. (13) can be got:

$$\tilde{I}(u, v) = \exp\big[i\pi\lambda DM(u^2+v^2)\big] \times \\ \times \iint T(x, y)T^*(x - \lambda Zu, y - \lambda Zv) \times \\ \times \exp\{-2\pi iM(ux + vy\}dxdyS(\frac{Z}{D}u, \frac{Z}{D}v). \quad (13)$$

In first part of Eq. (13), it is the expression of Fourier transform of image plane intensity on condition of an ideal point light sources, it has a relatively mature and accepted simplified expression as follows [12–14]:

$$\tilde{I}_{\text{point}}(u, v) = \exp\big[i\pi\lambda DM(u^2+v^2)\big] \times \\ \times \iint T(x, y)T^*(x - \lambda Zu, y - \lambda Zv)\exp\{-2\pi iM(ux + vy\} = \\ = \delta(u, v) + 2\sin\big[-\pi\lambda ZM(u^2+v^2)\big](u, v) - \\ - 2\cos\big[-\pi\lambda ZM(u^2+v^2)\big](u, v). \quad (14)$$

In this Eq. (14), $M = Z/D$ is the magnification, $\Phi(u, v)$ is the Fourier transform of the object phase shift, $\mathrm{H}(u, v)$ is the Fourier transform of the object absorption, $\sin\big[-\pi\lambda ZM(u^2+v^2)\big]$ is the phase modulation function under the conditions of the ideal coherent of point source. Combine Eq. (13) and Eq. (14) together, the Fourier transform of image intensity can be expressed as a simple form:

$$\tilde{I}(u, v) = S(\frac{Z}{D}u, \frac{Z}{D}v)\,\tilde{I}_{\text{point}}(u, v). \quad (15)$$

The impact of the light source radius on the phase contrast imaging system, in the frequency domain, can be described as the Fourier transform of the light intensity angular distribution function multiply the image intensity Fourier transform of the ideal fully coherent conditions. Therefore, in order to study the phase modulation effect of the light source radius individually, substitute Eq. (14) into Eq. (15), the integral phase contrast modulation transfer function (IPC–MTF) can be defined as

$$\mathrm{MTF}_{\mathrm{IPC}} = S(\frac{Z}{D}u, \frac{Z}{D}v)\sin\big[-\pi\lambda ZM(u^2+v^2)\big]. \quad (16)$$

To calculate the $\mathrm{MTF}_{\mathrm{IPC}}$, the light intensity distribution can be considered uniform for typical circular light source [15], and the light intensity distribution function can be expressed as Eq. (17), its Fourier transform is Eq. (18).

$$Circle\,(\frac{r}{R_0}) = \begin{cases} 1 & r \le R_0 \\ 0 & r > R_0 \end{cases}, \quad (17)$$

$$S(\frac{Z}{D}u, \frac{Z}{D}v) = \frac{1}{\sqrt{u^2+v^2}}J_1(2\pi ZR_0)\sqrt{u^2+v^2}\,/\,\mathrm{R}). \quad (18)$$

In the Eq. (18), J_1 first–order Bessel function, so the integral phase contrast modulation transfer function (IPC–MTF) described in Eq. (16), can be specifically written as a more specific shape:

$$\mathrm{MTF}_{\mathrm{IPC}} = \frac{1}{\sqrt{u^2+v^2}}J_1(2\pi ZR_0)\sqrt{u^2+v^2}\,/\,\mathrm{R}) \times \\ \times \sin\big[-\pi\lambda ZM(u^2+v^2)\big]. \quad (19)$$

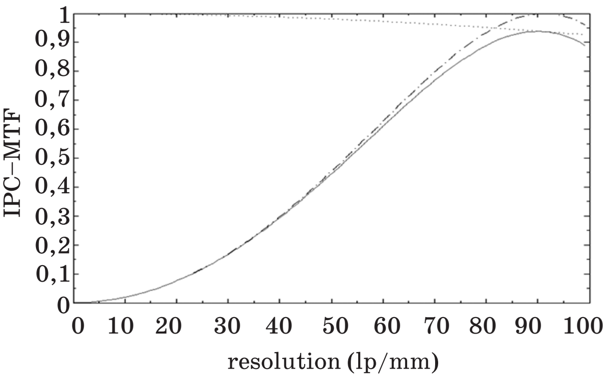

Fig. 2. Light source radius is 5 μm.

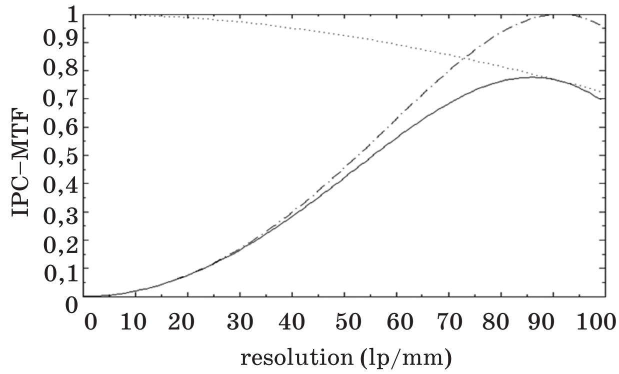

Fig. 3. Light source radius is 10 μm.

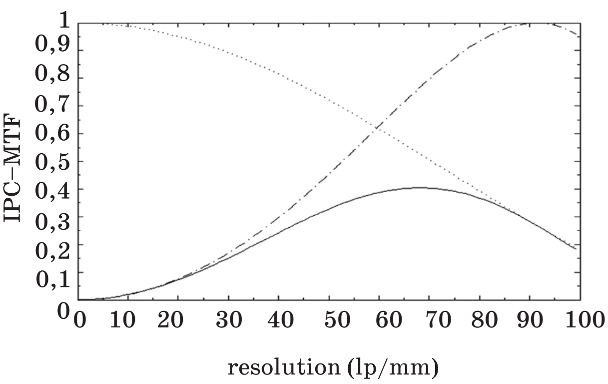

Fig. 4. Light source radius is 20 μm.

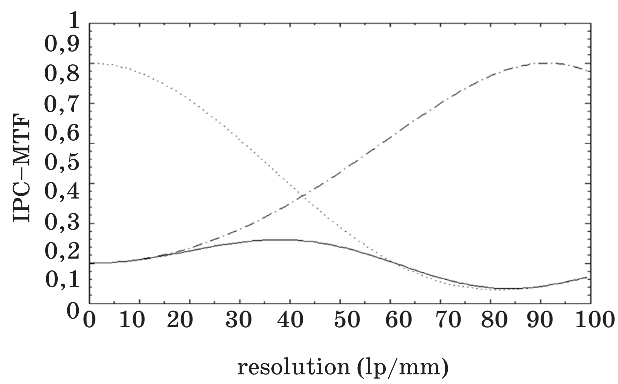

Fig. 5. Light source radius is 40 μm.

3. The simulation and experiment results

3.1 The impact of light source radius on the integral phase–contrast modulation transfer function

According to the above theoretical model, set the parameters unchanged, just change the light source radius, the results are shown in Fig. 2–5. In these figures, the solid line indicates the integral phase-contrast transfer function curve, dotted line indicates the phase contrast transfer function under the conditions of ideal coherent light source, dashed line indicates the space modulation function curve of the light source size itself. Comparing these curves, we can find that the influence of light source size on the integral phase contrast transfer function is obvious. Therefore, the focus size is a critical system indicator for the micro-focus X-ray phase contrast imaging system, smaller focus size can upgrade the overall system performance.

3.2 Choice of light source size

If the light source size is too small, the whole equipment cost will rise, and the luminous flux, as well as the entire tube power will be limited. Therefore, under the actual context of the specific experimental conditions, it is difficult to determine the appropriate focus sizes under the premise of the overall phase-contrast imaging performance. To this end, we set up an experiment using the detector resolution 50 lp/ mm, fix the object to detector distance, change the light source to object distance respectively at 0,2, 0,4, 0,6, 0,8, 1,0, 1,2 meters, the IPC-MTF changes with the light source radius are shown in Fig. 6. After that we fix light source to object distance, change the object to the detector respectively at 0.2,0.4,0.6,0.8,1.0,1.2 meters, the IPC-MTF changes with the light source radius are shown in Fig. 7.

3.3 The experiment results

The micro focus X-ray source was employed in this experiment according to the above theoretical

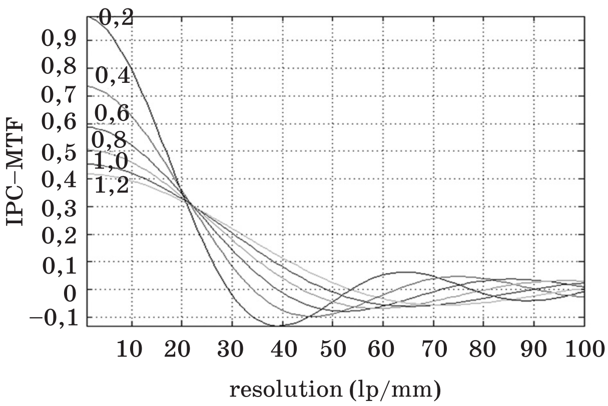

Fig. 6. Fix the object to detector distance.

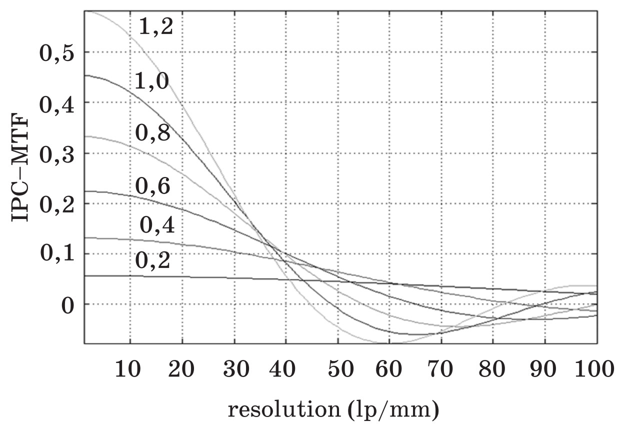

Fig. 7. Fix the source to object distance.

model, the sample was an optical fiber with the radius of 200 µm, the images shown in the Fig.8 and 9 are obtained when micro focus spot radius was set 40 µm and 20 µm respectively. In our experiment, the tube potential was 30 kV, the tube current was 250 µA, and other parameters ware set at the optimization way.

In the Fig. 9, micro focus spot radius was set 20 µm , the boundary and overall contrast can be seen clearly, while in the Fig. 8, micro focus spot radius was changed to 40 µm, the boundary and overall contrast are much less distinct, which validates the prediction results of the theoretical formula and analysis in this paper.

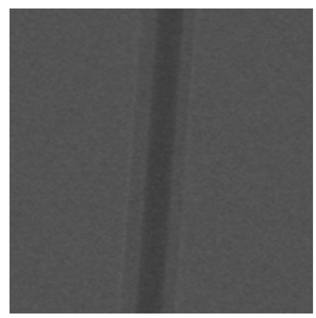

Fig. 8. The focus spot radius is 40 µm.

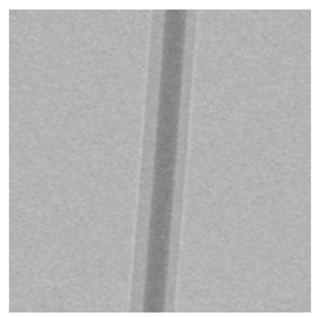

Fig. 9. The focus spot radius is 20 µm.

4. Conclusions

This paper considers the light source radius of actual micro focus X-ray phase contrast system, the impact of light source spatial coherence is analyzed based on free-space propagation of mutual intensity theory, then a new integral phase contrast modulation transfer function model is established. In the actual experimental system conditions, we propose the choice regulation of light source size, and give a quantitative basis and proposal.

On the basis of the research conclusion, we set the different experimental micro focus on the light source radius, the test results validate that the model and analysis proposed in this paper are correct. In the actual system design and parameter optimization process, there are many other factors need to consider such as light intensity, sample size, current size, all of these should be discussed in the future.

* * * * *

REFERENCES

1. *Pogany A.*, Rev. sci. instrum, 68(1997) 2774.
2. *Snigirev A.* Rev. sci. instrum, 66(1995)5486.
3. *Wilkins S.W.* Nature, 384(1996)335.
4. *Spanne P.* Med. Biol, 44(1999)741.
5. *Cloetens P.* Phys J. D: Appl. Phys,32(1999)145.
6. *Momose A.* Opt. Express, 11(2003)2303.
7. *Chapman D.* Nature, 373(1995)595.
8. *Montgomery D.S.* Rev. sci. instrum, 75 (2004)3986.
9. *Gureyev T.E., Pogany A., Paganin D.M.* Optics Communications, 231(2004)53.
10. *Shu-Ang Zhou, Anders Brahme*. Physica Medica, 24(2008)129.
11. *Chika Honda, Hiromu Ohara*. European Journal of Radiology, 8(2008)69.
12. *Zhi-Feng Huang, Ke-Jun Kang, Li Zhang*. Phy. Rev. A 79(2009)13.
13. *Fanbo Meng, Da Zhang a, Xizeng Wu*. Optics Communications , 282(2009)3392.
14. *Coan P., Gruener F., Glaser C., Schneider T.* Physics Research A, 608(2009)44.
15. *Olivo A., Rigon L., Vinnicombe S.J.* Applied Radiation and Isotopes 69(2009)1033.