ARTICLE IN PRESS

Precision Engineering xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Development of high-energy and high-resolution X-ray CT

Katsutoshi Sato[a], Makoto Abe[b,*], Toshiyuki Takatsuji[b]

[a] Hitachi Ltd., Saiwai-cho 1-1, Hitachi, Ibaraki, 317-8511, Japan
[b] National Metrology Institute of Japan (NMIJ), National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Umezono, Tsukuba, Ibaraki, 305-8563, Japan

ARTICLE INFO

Keywords:
Computed tomography
X-ray
High-energy
High-resolution

ABSTRACT

This paper introduces a novel high-energy and high-resolution X-ray computed tomography system called eXTRACT. Preliminary experimental testing was performed of the penetration capability and structural resolution achieved by the system, and the results are reported. The X-ray source realized both bremsstrahlung X-rays with an average energy of 1 MeV and the focal size of 100 μm at the same time. Using 970 physical channels of high-energy X-ray line detectors and a modified offset scanning method, the CT reconstruction of 4286 by 4286 pixels were achieved for a single sinogram from a single fan beam scanning. The performance was further investigated by scanning several material standards. The penetration capability of 400 mm or more, represented by a longitudinal dimension of the object, was recorded in case of scanning aluminum. The structural resolution of 0.1 mm by 0.1 mm line and space structure under the field of view size of 300 mm in the diameter is also verified.

1. Introduction

Advances in production engineering technology are allowing industrial products to become more complex in design and the associated geometrical features. Tactile coordinate measuring machines (CMMs) has widely been utilized in production engineering and the quality control. However, the range of geometrical features that can be extracted is limited by the sparse measurement points allocated to the CMM performance, especially the slow measuring throughput that the machines are able to reach. As products become more complex in the geometrical forms, evaluation of the full geometry is increasingly demanded.

There has been a technical trend in coordinate metrology away from sparse point measurement to point cloud measurement collecting a huge number of points by using measuring instruments such as optical scanners or X-ray computed tomography (X-ray CT) [1]. X-ray CT has been attracting growing interest in manufacturing industry [2] since it for the first time allows both the external geometrical features and internal features of a product to be measured [3].

X-ray CT, the development of which earned a Nobel Prize, was first applied to medical tomographic scans [4]. As the performance of the key components have improved and the cost has fallen, applications have been extended to non-destructive testing of industrial products [5]. Its applications include detection of voids in metal casts and identification of imperfection in assembly of industrial products. Industrial X-ray CT has now improved sufficiently to allow three-dimensional volume data to be collected and used to verify the geometry of industrial products. Several manufacturers have also launched dimensional X-ray CT that guarantees the traceability to the unit of length and the length measuring performance [6–10]. Dimensional X-ray CT is typically classified as a microfocus X-ray CT equipped with X-ray tube having the maximum tube voltage of 80 kV up to 450 kV. This limits the maximum penetration length to approximately 50 mm or 250 mm depending on an object being scanned made of steel or aluminum.

To allow larger objects to be scanned, an X-ray source with significantly higher penetration capability is required. One way of achieving this is the use of a linear electron accelerator (linac) [11,12]. Systems using this technology are classified as high energy X-ray CT. Such systems have been applied to CT scanning of a whole body of automobile [13] while there is a growing demand for systems that can resolve the fine structure of the object being scanned.

In this study, we developed a high-energy high-resolution X-ray CT system, named eXTRACT, realizing both the penetration capability and resolution simultaneously, which is difficult for existing X-ray CT. The paper introduces the key components of eXTRACT and reports preliminary experimental evaluations of its penetration capability and resolution performance.

* Corresponding author.
E-mail address: makoto.abe@aist.go.jp (M. Abe).

https://doi.org/10.1016/j.precisioneng.2018.06.004
Received 25 February 2018; Received in revised form 23 May 2018; Accepted 31 May 2018
0141-6359/

Table 1
Key measures of X-ray CT and performance index.

Key component of X-ray CT	Detaild characteristic	Performance index				
		Penetration capability	Structural Resolution	Signal to noise ratio	Duration of Scanning	Duration of reconstruction
X-ray source	Energy (Tube voltage)	○		○		
	Brightness (Tube current)	○		○		
	Focus size		○			
Scanner	Scanning strategy		○	○	○	
	Magnification variability	○	○			
X-ray detector	Image integral time	○		○	○	
	Collimation of incident X-ray		○			
	Elemental size		○	○		
	Dynamic range	○		○		
	Filtering		○	○		
Reconstruction	Voxel size		○			○
	Volume size of reconstruction					○
	Reconstruction algorithm					○
	Software error correction			○		○
Scanned object	Size			○		
	Material			○	○	
	Form			○		

2. Background of development

2.1. Performance tradeoffs

Table 1 summarizes major performance indices applied to the system components [14]. In most cases, there are tradeoffs between the indices; improvement against one measure is often associated with deterioration against another. For example, a certain minimum number of photons must be collected to suppress unwanted noise in the reconstructed X-ray CT image. However, increasing the number of photons collected also increases the time required to complete the scan. This tradeoff between indices has made the realization of an X-ray CT with both high energy and high resolution challenging.

The choice of X-ray sources for high-energy X-ray CT is limited in practice to synchrotron radiation or linac. The former typically requires the sort of large scale particle accelerator that was originally built for use in fundamental physics research, material analysis, and so on. Scanning must take pace in the immediate vicinity of the accelerator, making industrial use impractical. The linac has been more widely used in high-energy X-ray CT however the resolution that can be achieved is limited by the focal size of X-ray. This limit is approximately 2 mm, and it is known to be difficult to sharpen further.

High energy X-ray results in increased penetration length, but these high energy X-rays pass through the detector material that is supposed to capture them. It is therefore challenging to design a multichannel detector that combines increased sensitivity with increased spatial density.

2.2. Simultaneous accomplishment of high-energy and high-resolution

This goal requires two competing performance measures to be reconciled: penetration capability and structural resolution. The former can be achieved straightforwardly by increasing the photon energy of the X-ray source, while the dynamic range of the X-ray detector is typically improved by increasing the sensitivity to X-rays. The design of a high-energy X-ray CT with high resolution therefore requires the following factors to be considered:

a) The focal size of the X-ray source must be sharpened.
   The total brightness of the X-ray source will be reduced unless the X-ray intensity at the focal point can be significantly increased. However, this will tend to reduce the penetration length.
b) The cross-sectional dimensions of a single channel X-ray detector must be small enough.
c) The series of detector elements must be densely arrayed.

Achieving b) and c) may adversely affect the dynamic range of the detector. This may place limitations on the extent to which the effective structural resolution of the X-ray CT system can be enhanced. The simultaneous achievement of high energy and high resolution therefore requires an X-ray source with high energy and a fine focal size, and a multichannel detector with high sensitivity and a densely arrayed layout. In the next sections we introduce the key components on which our proposed X-ray CT system is based.

Design and target specification of high-energy and high-resolution X-ray CT were first time addressed through the present study with intention to meet demands from manufacturing industry for X-ray CT capable of scanning larger objects such as power train of automobile industry or aero industry. The typical requirements can be summarized as the structural resolution of 0.1 mm while having the penetration length of 400 mm or more for aluminum. Fig. 1 was drawn for sketching relation between the penetration length and the structural resolution of state-of-the-art X-ray CT intended for industrial use particularly in larger dimensions.

3. Overview of eXTRACT

An X-ray CT System consists typically of a few key components, that

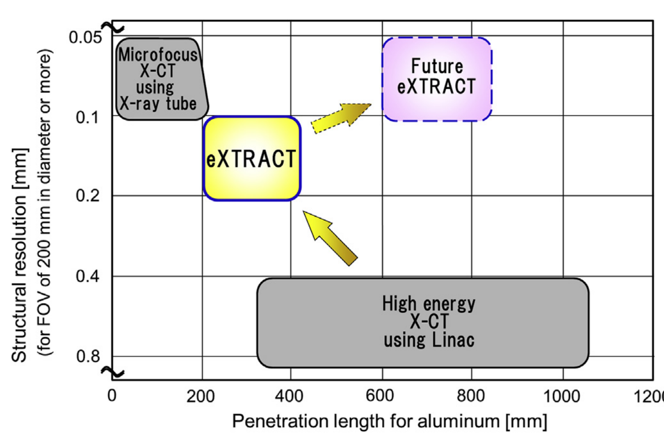

Fig. 1. Penetration length and structural resolution of X-ray CT intended for industrial use in larger dimensions.