An industrial CT system for monitoring a running aero-engine (Postprint)

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Abstract

In order to improve aerodynamic performance and efficiency, monitoring the geometry and position information of the internal structure with the aero-engine under various operational statuses is an important task. In this paper, a novel design of industrial computed tomography (ICT) system with a linac as x-ray source is proposed to complete the task. The major advantage of the proposed system is that it can provide visualized images of internal structures of the running aero-engine without physical disturbance, which makes it possible to extract the accurate geometry information. The main idea behind this design is to measure the projection data from various views for reconstructions making use of the rotations of the aero-engine blades, instead of the mechanical rotations in the conventional ICT system. However, due to high speed rotation of the aero-engine blades, the system faces more challenges than conventional ICT systems both in data acquisitions and reconstruction algorithms. The challenges and corresponding solutions are presented in this paper. In conclusion, the proposed ICT system provides a powerful tool for monitoring the running aero-engines.

Full Text

Preamble

An Industrial CT System for Monitoring a Running Aero-Engine

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Monitoring the geometry and position information of internal structures within an aero-engine under various operational statuses is crucial for improving aerodynamic performance and efficiency. This paper proposes a novel industrial computed tomography (ICT) system design employing a linac as an X-ray source to accomplish this task. The major advantage of the proposed system is its ability to provide visualized images of the internal structures of a running aero-engine without physical disturbance, enabling accurate geometry information extraction. The main idea behind this design is to measure projection data from various views by utilizing the rotations of the aero-engine blades themselves, rather than relying on mechanical rotations as in conventional ICT systems. However, due to the high-speed rotation of aero-engine blades, the system faces greater challenges than conventional ICT systems in both data acquisition and reconstruction algorithms. This paper presents these challenges and corresponding solutions. In conclusion, the proposed ICT system provides a powerful tool for monitoring running aero-engines.

Keywords: Dynamic imaging, Computed tomography, System design, Image reconstruction
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Introduction

Running aero-engine tests are essential experiments in aero-engine structure design and fabrication for improving efficiency, aerodynamic performance, and aircraft safety. For example, tip clearance has long been a technical challenge in aero-engine development. A 1% increase in compressor casing tip clearance decreases compressor efficiency by 1-3% [1], while excessively small tip clearance increases the probability of friction or collision between blades and casing, potentially causing serious accidents. Additionally, blade dimensions greatly affect engine aerodynamic performance. Therefore, monitoring internal geometry information of an aero-engine under various operating conditions is of great significance. However, measuring inner structures under high temperature, high pressure, and high rotating speed (10,000 rpm or higher) is extremely challenging using conventional methods. For instance, oil dirt contamination can reduce measurement accuracy of optical sensors [2], and eddy current measurement is restricted by the high temperatures of aero-engines [3]. Furthermore, it is neither convenient nor permissible to install detectors or sensors inside aero-engines because they disturb airflow distributions.

Currently, dimensional changes in blades under various operating conditions are checked through indirect measurements, which cannot provide visualized images, or through computer simulation, which cannot accurately replicate the complex real working environment. X-ray computed tomography provides accurate images without physically disturbing the object being inspected and is suitable for monitoring running aero-engine blades [4]. Another inherent advantage of X-ray process tomography is the hard-field character of X-rays, which enables clear images without blurs or artifacts. Hampel et al. developed a gamma-ray tomography system to measure fluid distributions in a rapidly rotating fluid coupling [5]. They designed an angle-synchronized trigger device to sort projection data acquired from their system [6] and successfully revealed fluid structure in the coupling under different rotating speeds. However, an aero-engine is far more massive and complicated than such fluid couplings, and numerous pipelines in the stationary parts introduce significant contamination to projections of the rapidly rotating blades. Additionally, determining projection angles and suppressing motion blurs pose challenges for X-ray tomography because the blades rotate much faster than the fluid coupling.

This paper proposes an innovative industrial computed tomography (ICT) system design for monitoring changes in the internal structure of a running aero-engine. This design makes it possible to obtain accurate images of internal structures under different operational statuses of the aero-engine and has the potential to derive tomographic information throughout the entire engine running test. Section II presents details about the system design. Section III analyzes three major challenges to the ICT system and proposes feasible solutions. Section IV demonstrates the feasibility of the ICT system and the effectiveness of the solutions through computer simulations and experiments. Finally, conclusions are drawn regarding the proposed ICT system and its major challenges.

II. Methods

A. System Design

Unlike the static scanning object in a conventional ICT system, aero-engine blades rotate rapidly during measurements. An ICT system has been developed to acquire images of rotating blades under steady operating states of an aero-engine. The main idea is to measure projection data using the blade rotation of an aero-engine with a stationary X-ray source and detector array [7, 8], rather than using mechanical rotations as in conventional ICT systems. As shown in Fig. 1 [Figure 1: see original paper], a 4 MeV electron linac X-ray source produces a sequence of X-ray beams pulsed at approximately 4 µs width while the blades rotate at approximately 10,000 rpm. On the opposite side, the detector array receives X-rays attenuated by the aero-engine, and the data are transmitted to a workstation for image reconstruction. A sensor monitors blade rotation fluctuation, and its signals are used for accelerator control.

In conventional ICT systems, projections from different views are acquired through step-by-step mechanical turntable rotations, with the linac triggered according to angle encoder signals. However, in this design, the object itself rotates. Two trigger modes are proposed (Fig. 2 [Figure 2: see original paper]): single-trigger and multi-trigger modes. In single-trigger mode, the linac generates a sequence of X-ray pulses with interval t_0 across several rotation cycles. Signals from the sensor are only used for estimating rotation speed, which is not strictly necessary, as trigger signals can also be sent manually. This mode is particularly useful when sensor signals are inaccurate or when installing such a sensor around the blades is not permissible. However, projection view accuracy is affected by speed fluctuation in this mode. In multi-trigger mode, the sensor sends a pulse signal to the system controller whenever a blade passes by, synchronizing the accelerator to blade rotations. Specifically, the controller triggers the linac with a proper delay of t and a period of T d according to rotation speed and ideal projection angles, using a programmable logic controller (PLC) to achieve this function. In this mode, uniform sampling is available even when rotation speed is not constant because the controller adjusts the delay time t according to speed fluctuations.

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B. Reconstruction Algorithm

The dynamic measurement procedure and rotating blades make recovery of internal structures more complex and difficult. Three major obstacles must be overcome. First, it is crucial to sort projections with corresponding projection views and ensure reconstructed image quality. Second, "blocked projections" must be corrected. Since all projections are acquired using rotating blades, stationary casing and pipelines around the blades manifest as block contaminations in projection data, introducing significant artifacts in final results. Third, motion artifacts must be addressed. Due to high rotation speed, blades rotate through a certain angle during X-ray exposure, causing blurred edges. The following sections analyze these three challenges.

1. Determination of Projection Views In conventional ICT systems, exact projection views can be obtained from angle encoders on the mechanical turntable. However, in this design, the angle sampling interval is determined by the product of rotation speed and time interval between adjacent X-ray pulses. Determining exact projection angles is key to achieving high-quality images. In single-trigger mode, the linac produces pulsed X-ray beams at a given frequency, and sampling angles can be estimated from accelerator frequency and blade rotation speed if the latter is constant. However, due to rotation speed fluctuation, projection angles are often slightly inaccurate, and errors accumulated across several rotation cycles eventually lead to obvious stripe artifacts in reconstructed images. To reduce accumulated errors, a posterior correction-based method using statistical properties of projections is proposed. Projections measured from the same view or from very close views should exhibit very high similarity, measurable by cross-correlation coefficient or standard deviation. For example, in single-trigger mode, after M rotating cycles, the Nth X-ray pulse is produced when blades rotate to the same position where the accelerator generated the 1st X-ray pulse, making the projection quite similar to the 1st projection. The angle sampling interval $_0$ can be estimated by Eq. (1), and nth projection views can be calculated by Eq. (2).

$$\theta_0 = 360M/N, \quad \theta_n = (n-1)\theta_0.$$

From Eq. (2), projection view error increases with n. To suppress accumulated errors, adjacent projections are grouped, dividing projections into several groups. Images are then reconstructed with these projections respectively. While limited projection data suppresses accumulating errors, insufficient data may affect image quality. To make full use of all projections, registrations between these pre-reconstructed images are performed to acquire relations of projection angles (offset angles) among different projection groups. Finally, all projection data are reorganized for reconstruction while greatly limiting accumulating errors. The complete workflow is presented in Fig. 3 [Figure 3: see original paper].

With a sensor to detect blades, multi-trigger mode can be adopted, and uniform angle sampling can be achieved by the controller, in which a PLC adjusts delay time and pulse frequency adaptively to match changing rotation speed. Projection views incorporating sensor information are more accurate. If speed changes are too large, projections obtained far from ideal positions can be removed or re-measured.

2. Correction of Blocked Projections Block contaminations in projection data are caused by stationary casing and complicated pipelines around the blades. The source-detector and block components remain static throughout the scanning procedure, meaning block components to a specific detector at different views are constant. The discrete imaging model expression at the ith projection view to the jth detector can be given as $H_{i,j}f + b_j = p_{i,j}$, where H is the projection operator, f is the image datum, b is the block term, and p is the projection datum. Details of the reconstructed image using contaminated projections are seriously corrupted by these artifacts, making it hard to determine blade edges.

An interaction-based method with a prior image is developed to address this problem. Contributions of block components will be removed or estimated from acquired projection data. This paper incorporates a prior image to achieve this goal. Before dynamic measurements, a static aero-engine is scanned by conventional ICT, and an image without blocks is reconstructed, serving as the prior image f_{prior}. The prior image f_{prior} is used to simulate the contribution of $H_{i,j}f$ for estimating block components, though some detail differences exist. Registration between the reconstructed image and prior image is essential before estimation because they are generally not at the same location. Serious artifacts besides deformations can appear in the reconstructed image, making it difficult to apply auto-match technologies such as the Scale-Invariant Feature Transform (SIFT) method [9] for registration. Hence, interaction is introduced into the registration procedure.

A forward-projection of the matched prior image $\tilde{f}_{prior}$ with practical scanning configuration parameters is then performed. The block components of the jth detector, $\tilde{b}_j$, can be estimated by:

$$\tilde{b}_j = \frac{1}{N_{view}} \sum_{i=1}^{N_{view}} \left(p_{i,j} - H_{i,j}\tilde{f}_{prior}\right). \quad (5)$$

The $\tilde{b}_j$ values from Eq. (5) are used to obtain corrected projection data for final image reconstruction:

$$\tilde{p}_{i,j} = p_{i,j} - \tilde{b}_j.$$

The summarized workflow is shown in Fig. 4 [Figure 4: see original paper].

3. Suppression of Exposure Blurs Exposure blurs in final reconstructed images result from high rotation speed, causing blades to rotate through a certain angle during X-ray exposure. This significantly degrades image spatial resolution and greatly limits ICT capability for high-precision measurements. Therefore, blade rotations during X-ray exposure must be considered in the reconstruction method. An iterative reconstruction method is proposed based on discretization of the X-ray exposure procedure. The main idea is to discretize the dynamic X-ray exposure into several virtual conventional exposure child procedures. Specifically, this physical procedure is divided into M virtual conventional static exposure processes. In different sub-processes, blades rotate to different positions as:

$$I_j = I_0 \exp\left(-\sum_{i=1}^{M} H_{i,j} f\right), \quad p_j = -\ln\frac{I_j}{I_0} = \sum_{i=1}^{M} H_{i,j} f, \quad (6)$$

where subscripts j and i indicate the jth X-ray path and the ith sub-process of virtual conventional static exposure, respectively. In fact, $H_{i,j}$ is the system matrix of the jth detector at the ith sub-process.

Equation (6) presents a nonlinear problem that raises great challenges for conventional reconstruction methods, which assume a static scanned object. However, it can be approximately converted to a linear problem using Taylor expansion with a good initial guess f_0:

$$H_j df = p_j, \quad \text{where} \quad H_j = \sum_{i=1}^{M} \left[\exp(-H_{i,j} f_0) H_{i,j}\right], \quad p_j = \sum_{i=1}^{M} \exp(-H_{i,j} f_0) - \frac{I_j}{I_0}. \quad (7)$$

Note that the difference image df rather than f is calculated in each iteration. Therefore, the initial guess f_0 should be updated after each iteration by $f_0 = f_0 + df$.

According to our research, initial guesses can come from either a prior image or the blurred image. The problem can then be solved by widely used algebraic reconstruction methods with only simple modifications to the system matrix and projection data as shown in Eq. (7).

In summary, Fig. 5 [Figure 5: see original paper] shows the total flowchart for a comprehensive demonstration of system challenges and corresponding solutions.

III. Simulations and Experiments

A. Numerical Simulations

Computer simulations first validated the feasibility of the single-trigger mode of the proposed system. As shown in Fig. 6 Figure 6: see original paper, a simple phantom was designed to simulate aero-engine blades. Angle intervals of samplings were estimated based on projection similarities as mentioned above, but errors in estimated angle intervals were inevitable. Errors accumulated in projection angles because they were calculated by accumulating the angle intervals. As shown in Fig. 6(b), image quality reconstructed with rough projection angle positions degraded significantly, greatly influencing subsequent quantitative analysis. In contrast, visible improvements in image quality were achieved using the proposed posterior correction-based method. The relative error reduced to 48% of the conventional approach because the maximum estimated errors of projection angles decreased from 4.3° to 1.61°. Hence, posterior correction of projection angles is essential to guarantee image quality in single-trigger mode when monitoring running aero-engine blades.

Next, an air blower was used as a phantom to demonstrate the effectiveness of the method for suppressing exposure blurs. However, air blowers rotate at approximately 2,900 rpm rather than the 10,000 rpm of aero-engine blades. To simulate projections of real rotating aero-engine blades, successive projections were accumulated to simulate significant rotational movements during X-ray exposures. Results from conventional method and the proposed ICT are presented in Fig. 7 [Figure 7: see original paper].

Compared with the reference image, Fig. 7(b) shows significant exposure blurs and decreased contrast-to-noise ratio (CNR) when using conventional reconstruction method due to rotations during X-ray exposure. In contrast, images reconstructed by our method exhibit sharp edges (Figs. 7(c) and 7(d)). For quantitative analysis, CNR at blade edges was calculated. The CNR values for Figs. 7(b), 7(c), and 7(d) were 50, 70, and 80, respectively. Thus, more virtual child exposures used to simulate actual exposure yield better results, though with heavier computational cost. In practice, the number of virtual exposures is determined by tradeoffs between image quality and computation. Development of corresponding accelerated methods using GPU will be part of future work due to high parallelism. The high-quality image makes it possible to detect minor changes in internal structure of running aero-engines and demonstrates the effectiveness of our method in suppressing exposure blurs.

B. Experiments

To demonstrate feasibility of the proposed ICT system and effectiveness of the methods, a 2,900 rpm air blower was scanned (Fig. 8 [Figure 8: see original paper]). A laser sensor mounted on the casing generated a pulse when the blade tip passed by. To simulate pipelines of an aero-engine, several steel columns were placed randomly around the air blower. Multi-trigger mode was adopted in this experiment. With the 4 MeV linac' s maximum frequency of 250 Hz, 4 samplings were acquired in each cycle, completing 1,024 measurements in 256 cycles. The total scanning time was less than 6 seconds, significantly faster than conventional CT measurements, making it possible to achieve several tomographic images during the test.

First, a conventional ICT scan was performed with the air blower static, and internal structure under idle state was reconstructed (Fig. 9 Figure 9: see original paper). Next, dynamic measurements were conducted with the air blower rotating at approximately 2,900 rpm, and internal structure was reconstructed with reorganized projection data (Fig. 9(b)). However, significant ring artifacts caused by steel columns corrupted image quality (Fig. 9(d)). Projection data were then corrected using the interaction-based method with the static image as prior image. Figures 9(e) and 9(f) show that the reconstructed blade shapes differ significantly from the prior image, so registration was performed according to major structures such as the air blower casing. The final image (Fig. 9(g)) reconstructed using projections corrected by the interaction-based method was almost free of ring artifacts, and main differences in blade shapes were well recovered. These improvements in image quality are meaningful for geometric measurements. However, some local artifacts remained due to systematic errors such as sensor signal fluctuation, mechanical vibration, and other engineering issues. Future work will adjust the experimental design with enhanced sensor stability for further image quality improvement.

IV. Conclusion

This paper presents an innovative X-ray process tomography system design to obtain internal structure images of running aero-engine blades, making it possible to extract accurate geometry information of internal structures under different operational statuses. Compared with conventional measurements, it has potential to achieve high-quality images under harsh conditions without physical disturbance. The proposed system can achieve image sequences for each steady state during running aero-engine tests, which is meaningful for aero-engine design and control, though this paper only addresses certain steady states. Its advantages of non-contact and visual imaging make it suitable for monitoring internal structure changes in running aero-engines.

Three major challenges caused by dynamic measurements and rapid rotational movements are discussed, and feasible solutions are proposed. The effectiveness of these methods is demonstrated through simulation and experimental results.

These basic studies are meaningful for future system implementations. Although tip clearance measurement was not completely solved, the proposed system with corresponding algorithms provides a new powerful CT-based tool not only for dynamic tip clearance measurement but also for inspecting internal geometry and position changes. Furthermore, our system design and solutions are not limited to monitoring running aero-engine blades and can be expanded to other X-ray process tomography applications for surveying internal structure changes in rapidly moving objects, such as gas turbines or steam turbines.

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Note: Figure translations are in progress. See original paper for figures.