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Potential of Computed Tomography for Inspection of Aircraft Components[†]

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ABSTRACT

Computed Tomography (CT) using penetrating radiation (x- or gamma-rays) can be used in a number of aircraft applications. This technique results in 3D volumetric attenuation data that is related to density and effective atomic number. CT is a transmission scanning method that must allow complete access to both sides of the object under inspection; the radiation source and detection systems must surround the object. This normally precludes the inspection of some large or planar (large aspect ratio) parts of the aircraft. However, we are pursuing recent limited-data techniques using object model information to obtain useful data from the partial information acquired. As illustrative examples, we describe how CT was instrumental in the analysis of particular aircraft components. These include fuselage panels, single crystal turbine blades, and aluminum-lithium composites. These tests were performed by the members of the Nondestructive Evaluation Section at the Lawrence Livermore National Laboratory (LLNL) where we have been actively working in CT research and development. The aerospace applications can represent various phases of the design, manufacture, assembly, test, and retirement of various components and assemblies.

1. INTRODUCTION

X-ray computed tomography (CT) has seen increasing use in an ever broadening array of industrial and military applications. Improvements in source, detector, and computational technology has made CT a more feasible and affordable option for nondestructive evaluation. First used in the 1970s as a medical diagnostic tool, CT was adapted to industrial and other nonmedical purposes in the mid-1980s. Single projection radiography hides crucial information—the overlapping of internal structures obscures their features and their depth—whereas CT was developed to retrieve 3D information of obscured internal objects. This capability of CT to capture internal features can be applied to a number of inspection and characterization needs for aging aircraft. In all cases, we will be referring to the attenuation of x-rays, as opposed to other penetrating radiation, for performing the imaging.

For CT, several radiographic images (or projections) of the object are acquired at different angles, and the information collected by the detector is processed in a computer. The final 3D image, generated by mathematically combining the radiographic images, provides the exact locations and dimensions of external and internal features of the object. Over the past five years, we have investigated and implemented many computed tomography methods. Our CT R&D efforts have been concentrated into three main areas, (1) scanners, (2) software tools, and (3) applications. The first two areas are briefly discussed in the next section.

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We choose to categorize nondestructive evaluation problems into two classes. The first, referred to as *inspection problems*, require defect (e.g., flaws, cracks, voids, and inclusions) recognition and dimensioning. The second, referred to as *material characterization problems*, require quantitative materials analysis (e.g., density/atomic number gradients and/or inhomogeneities, and radioisotope assay). Application of CT by others have ranged from using protons to image objects as small as a 30- μm o.d. capillary tube¹ to using high energy (60-MV) x-rays to image a phantom that is radiographically equivalent to the Challenger and Titan solid rocket motor². In the next section, we will describe the CT theory, discuss some of the scanners we use in our studies, and describe some of the issues to be addressed when processing CT data. We also have studied a wide range of applications using CT. In the Applications section we discuss three representative imaging problems: (1) fuselage panels; (2) airframe measurements; and (3) jet engine turbine blade inspection. We follow this with a discussion of some of the future issues and summarize the usefulness of CT for aircraft imaging applications in the last sections.

2. COMPUTED TOMOGRAPHY OVERVIEW

2.1 CT scanners at LLNL

CT systems require four main components: (1) a source; (2) a detector; (3) an object manipulator; and (4) one or more computers. These main components have been configured into eight different CT scanning systems in routine use within the Nondestructive Evaluation (NDE) Section at LLNL. (The CAT in their names is a vestige of the earlier term computerized *axial* tomography). Four are single-detector, discrete-beam scanners: Pencil-Beam CAT (PBCAT); a transportable CAT scanner (CATalyst); Medium-Energy CAT (MECAT); and Active and Passive CT (A&PCT)*. These scanners use x- and/or γ -ray sources with an energy-discriminating detector to provide high purity CT reconstructed images.³⁻⁶

The other four scanners employ multi-element detectors and use fan- or cone-beam geometries or both: Video CAT (VCAT); MicroCAT; High-Energy CAT (HECAT); and Linear-detector array CAT (LCAT). These scanners use x-ray machine sources and multi-element detectors. The detectors use a scintillating glass material to convert x-rays into visible light that is detected by light sensing detectors (e.g., charge coupled device cameras). These detectors integrate the entire energy spectrum and their CT reconstructed images do not provide quantitative material information as do the energy discriminating detector scanners. The virtue of these multi-element detectors scanners is that they are fast and provide high spatial resolution images.^{11,14-16}

All of our scanners are designed for modular assembly so that improvements in any one component can be easily incorporated. For example, this has been advantageous in adapting our area-array detector scanners with the new scintillation glass on the market and new charge couple device (CCD) cameras.³ The scanners vary in their energy resolution (none to high—200 eV), energy range (6 keV to 9 MV), spatial resolution (50 μm to 50 cm), and speed (a few seconds to several days) as well as data acquisition modes. This includes first (translation and rotation with a single detector), second (translation and rotation with a multi-element detector), and third (rotation only with a multi-element detector) generation, 1D and 2D projection data acquisition. The spatial resolution and energy range for which our scanners are operational is depicted in Fig. 1.

* Active and passive are the more commonly used terms for the intended application of this scanner instead of transmission and emission CT, respectively.

Most CT scanners measure x-ray and γ -ray intensities. Typically, both incident, I_0 , and transmitted, I , intensity values are used to calculate $\ln(I_0/I)$ for each projection or view. This ratio is referred to as the line integral or ray sum, g , along some ray path (the line from a source to a single detector; see Fig. 2). Data preprocessing consists of the sometimes elaborate steps involved in calculating ray sums from intensity data. Three properties of ray sums are particularly important:

- The geometry of the ray paths (i.e., the source and detector positions in the object coordinate system) must be completely known;
- At any given geometric position, the incident and transmitted intensities must have been faithfully measured and recorded;
- All preprocessed detector responses to a given energy must be identical; the responses of individual detectors therefore need to be balanced.

Since each procedure accommodates some physical characteristic of the source and detector system, each scanner dictates specific preprocessing methods and the number of operations. These preprocessing steps depending on the system may include restoring ray-path geometry; correcting glare and blur, dark current, and detector non linearity; balancing detectors; and normalization to the incident intensity, I_0 .^{9,10}

Next, the image must be computationally reconstructed from the ray sums to obtain an estimate of the x- and γ -ray attenuation cross section per unit volume within the object. We have two reconstruction methods: slice for 2D, and volume for 3D.^{3,9} When the 1D sinogram data are complete, the filtered- (FBP) and convolution-backprojection (CBP) algorithms perform best for parallel- and fan-beam projections, respectively. For incomplete data, we use any of several model-based reconstruction codes.¹¹ For 2D-parallel-beam sinogram image reconstruction, the 2D parallel reconstruction algorithms (typically FBP) are used to reconstruct each slice independently. These results may be rendered into a 3D or volume image. For cone-beam sinograms, we use 3D reconstruction methods that directly reconstruct the volume image. Our methods employ Feldkamp and Grangeat algorithms.^{12,13}

We use a variety of software tools to display the CT data, analyze the reconstruction algorithms, and perform detailed analyses of the reconstructed images.^{9,14,15} Overall visual displays of the image are sufficient to reveal large flaws such as voids or inclusions. However, we typically need more exact information. We determine the magnitude of these and other features more exactly by examining 1D profiles of the data. This reveals small variations from image to image and within an image. Dimensional information currently is done using a suite of software tools. We are upgrading these tools to make dimensional measurements more user friendly and to aid in converting the CT data into computer aided design (CAD), computer aided manufacturing (CAM), and computer integrated manufacturing (CIM) compatible data sets.

Several issues direct our R&D of CT scanners and algorithms. The intended application of the scanner dictates the spatial, contrast, and energy resolution required.¹⁶ Speed is also a concern and includes data acquisition times, and computational time requirements for reconstructing, displaying, and analyzing the CT image. We are striving for improvements in, and better understanding of, the relations among these four performance parameters: spatial resolution, image contrast, energy resolution, and speed.

It is not possible to optimize all performance parameters simultaneously, so judgments must be made of which to emphasize. For example, given a source/object manipulator/detector scanner configuration improvements in the energy resolution parameter typically results in better spatial and contrast resolution but at the cost of speed. Thus if speed is not so important for a particular application, energy discrimination is a useful way to go.

2.2 CT measurements

X-ray and γ -ray transmission CT scanners measure the removal of incident radiation by objects along straight-line paths (Fig. 2). The data measured are the photon intensities of the incident beam, $I_0[S(E),L]$, and the transmitted beam, $I[S(E),L]$, that was attenuated by the object along each ray path L for photon energy spectrum $S(E)$. The photon spectrum depends on the source energy distribution and detector efficiency.

The quantity that is reconstructed in x- or γ -ray CT is the attenuation value, $f[S(E),x]$ for some volume element, or voxel, at location $x = (x, y, z)$ with dimensions $\Delta x, \Delta y, \Delta z$ within the object. The reconstruction algorithms require line integrals, also called ray sums, for many ray paths defined as

$$g[S(E),L] = \left[\int_L f[S(E),x] du \right], \quad (1)$$

where du is the incremental distance along L . These ray paths are determined from the measurements through the Beer's law relationship

$$g[S(E),L] = \ln \left\{ \frac{I_0[S(E),L]}{I[S(E),L]} \right\}. \quad (2)$$

These ray sums over many paths are needed to reconstruct $f[S(E), x]$. For 2D parallel CT image reconstructions (z fixed), we often represent L by the ordered pair (s, θ) , where $s = x \cos \theta + y \sin \theta$ (Fig. 2). The set of parallel ray sums at one angle θ is collectively called a parallel projection. Likewise, the set of all parallel projections over a 180° angular range is called a parallel sinogram. The word sinogram refers to the fact that a single point within the object traces a sinusoidal curve over the projections.

The interpretation of the reconstructed value, $f[S(E), x]$, depends critically upon the data acquisition hardware (i.e. the source and detector used, not so much the geometry). Conventionally, industrial and medical CT use an x-ray machine source with a broad energy spectrum and a multi-element, current-integrating (non-energy discriminating) detector (e.g., a scintillator coupled to a solid state linear array detector) that integrates photons over all energies. The measurements of $I[S(E),L]$ and $I_0[S(E),L]$ are integrals over the entire energy spectrum, weighted by the quantum efficiency of the scintillator and the detector, $W(E)$, limited by the spectral range of the system. In this so-called *polyenergetic* case, the resultant attenuation image is therefore given by

$$f[S(E),x] = \int_0^{E_{\max}} W(E) S(E) \mu[\rho(x),Z(x),E] dE, \quad (3)$$

where μ is the linear attenuation coefficient, which is a function of volume density, r , the atomic number, Z , and E . Note that the resultant attenuation value is integrated and weighted over the entire energy spectrum. Thus, the quantitative calculation of ρ or Z , or even μ is impossible from this one reconstructed image.

Without a number of additional measurements using known standards, it is difficult to assign an absolute magnitude to the reconstructed values.^{17,18} In fact, only a relative measure of μ is the usual output of conventional CT scanners. Scanners that produce a relative measurement of μ usually perform well for nonintrusive inspection. This is mainly due to the fact that these scanners result in higher spatial resolution images than obtained with energy discriminating scanners. Since defect recognition and dimensioning are usually binary in nature the slightly higher systematic errors usually found in these scanners typically do not interfere with this type of analysis. On the other hand, material characterization problems require very high image purity (i.e., low systematic errors) and thus we typically use our energy-discriminating scanners to study this class of NDE problems as discussed below.

Our single-detector, energy-discriminating detector scanners differ from the conventional scanners in that they discriminate between photons of different energies. In this so called *monoenergetic* case, the resultant image is obtained for a single energy region (or characteristic peak) where the reconstructed image is given by

$$f(E, \mathbf{x}) = \mu[\rho(\mathbf{x}), Z(\mathbf{x}), E].$$

(4)

Therefore, the resultant voxel is *directly* a spatially discrete quantitative measurement of the linear attenuation coefficient at one energy E ; that is, there has been no integration over the energy spectrum, $S(E)$.

This value at each voxel can be compared to tables of cross sections,¹⁹ and can be manipulated as exactly the product of the sum of the mass absorption coefficients (according to the chemical formula of the voxel) multiplied by the density.¹⁷ No additional calibration measurements are necessary. Consequently, ratios and differences of CT reconstructed images at different energies reduce to simple functions that can be used to calculate the Z and r for each voxel. This data set is useful for flaw detection, dimensional measurements and material characterization. However, spatial resolution is usually more coarse because of time constraints than when using the multi-element detector scanners. On the other hand, material characterization problems require very low systematic errors; thus we typically use our energy-discriminating scanners to study this class of NDE problems.

The strength of the CT technology is its nonintrusive, non contact imaging and its ease of interpretation. CT can image the internal structure of complex obscured objects as well as external dimensions. The internal views of the objects are dimensionally correct, and the picture-element (pixel) variations are reliable and accurate and reflect the variation in material composition and/or density per voxel. Although not common, fieldable CT systems have been used to rapidly inspect trees and telephone poles *in situ*.^{20,21} It is thus known that CT can be designed to be economical, flexible, and weather tolerant. Furthermore, CT is a powerful NDE tool that—coupled with other NDE techniques—results in a better understanding of the difficult to interpret NDE techniques as well as the object itself.

It is useful to point out that the variation in CT reconstructed images is a function of three components: (1) measurement errors in the CT data (i.e., photon-counting statistics and systematic errors, e.g., electronic noise, and mechanical and geometrical uncertainties), (2) image reconstruction errors, and (3) deviations in atomic number Z and density ρ within the object. A knowledge of how the features observed in CT images relate to one or another of these three categories is fundamental to accurate interpretation of CT inspections. We have contributed to delineating these three different sources of variation in CT images.^{22,23}

3. CURRENT APPLICATIONS

We have used our several CT systems in a variety of applications, and we will describe three such examples applied to aircraft applications. Although virtually all of the experiments we perform are done on an experimental scale, they can and are being adapted to full-scale use within the laboratory and in production settings, in which case we typically work with vendors to develop the capability. Our CT efforts for inspection of aircraft components has been due, in large part, to the current availability of national laboratory resources for improvements in U.S. private sector economic competitiveness. However, in spite of the rapid changes occurring within the U.S. and more specifically the national laboratories, due mostly to the thawing of the cold war, the concept of dual (military and commercial) use technologies remains a high priority. Thus we also must continue to provide unique inspection capabilities for national laboratory programmatic research, development, and application.

3.1 Fuselage Panels

Recently, we have been conducting a long-term study of aircraft structures for the Federal Aviation Administration (FAA). The goals of this study have been to investigate reasonable NDE techniques for such structures and develop methodologies for their widespread use. Initial studies have focused on the inspection of aircraft fuselage panels for corrosion. A "reasonable" method for NDE should be access-independent, reliable and accurate, economical, flexible, weather-tolerant, fast, rugged, and capable of objective interpretation. It should identify the areas of corrosion, quantify the extent of damage, and intelligently present this information to the operator. Some of the methods under study at this time are ultrasound, infrared imaging, digital radiography and CT. While CT is more reliable, accurate, and capable of objective interpretation than some of the other techniques, it is not well-suited for the other criteria mentioned above. Therefore, we use the CT measurement in our experiments to verify the results of the other techniques; it can be used as a final arbiter for nondestructive evaluation of these fuselage panels. Fieldable CT scanners for *in situ* aircraft inspections are plausible but present some engineering challenges.

To evaluate the efficacy of CT in detecting and quantifying corrosion, we have scanned an F-111 wing panel that shows some of the effects of corrosion. An example radiograph and CT slice of such a panel is shown in Fig. 3. These scans were performed on our LCAT scanner at 160 kVp and 1.9 mA. The digital radiograph at right clearly shows the corrosion area of interest, while the CT slice through that area gives a better view of the void volume. Furthermore, multiple 2D CT images can be used to analyze this data in all three dimensions to better interpret the volumetric properties of corrosion.

These tests, while showing the excellent capability of x-ray attenuation measurements for finding voids due to corrosion, also point out the weaknesses of these techniques in scanning actual aircraft. Radiography and CT require transmission of the x-rays through the part, and therefore require complete access to both size of the structure. This is possible for small test samples such as those in Fig. 3, but is often impractical for complete airframes. For intact fuselage panels, the x-ray source and detector must be on opposite sides of the panel and, for CT, must have coupled movements with access completely around the panel. In addition, without complete access to the panel from within the wall, CT reconstructions must deal with incomplete data while doing reconstructions. For these reasons, CT is more of a laboratory device at this time.

A related problem, also apparent in Fig. 3, is the fact that many aircraft parts have a large aspect ratio; i.e., the width is much larger than the length. This poses difficulty in setting the x-ray parameters so that, for long paths, the x-rays penetrate the part while, for short paths, there is sufficient contrast to distinguish internal features. Without proper adjustment of parameters or with large aspect ratios, the CT reconstructions can have limited data or can produce some streaking artifacts. Special algorithms are capable of producing reasonable reconstructions in these cases, but they require knowledge of the part structure and often involve increased computational load.¹⁹

3.2 Airframe Measurements

Aluminum airframe components have been studied by our group for determining the dimensional accuracy of CT. The overall goal of the project is to develop an alternative method to coordinate measurement machines (CMM) that is both non-contact and can measure dimensions of internal structures. This would be attractive in a number of applications related to the inspection of aging aircraft. Not only could manufacturing tolerances be verified, but also changes over time could be monitored for the effects of wear or material loss. In addition, measurements could be used for verifying, or even generating, CAD models of aircraft parts.^{24,25} Also, instead of replacing a CMM, the CT data could be used to develop new CMM training methods—currently a difficult task—in an automated fashion.²⁶

As an initial study of the capabilities of CT for dimensional measurements, we have performed some 3D CT scans of aluminum struts. Fig. 4 shows both a radiograph and a CT slice of one such structure. Outside wall thickness measurements are easily obtained for this part so that the CT data can be verified. Several methods for estimation of wall thickness are being applied and tested. These include nonlinear least squares estimation of the expected wall shape and differentiation techniques. In all cases, it is important to provide both the thickness estimate and some measure of the uncertainty of that estimate. Depending on the quality of the CT scan, thickness estimates can be made to accuracies of better than one pixel. Ensemble averages of many of these measurements is also provided by software. This study illustrates how CT data can be used to carefully gauge internal features of complex objects such as struts for dimensional accuracies.

3.3 Jet engine turbine blades

Both high and medium energy CT scanners are being applied to a variety of single crystal hollow core turbine blades.²⁷ These blades are required in modern high efficiency, low pollution jet engines where gas temperatures can exceed the melting point of the blade metal. In addition, the blades are expensive to manufacture, making destructive tests costly and inefficient. This work is being performed as a part of a Wright Patterson Air Force Base funded project. Southwest Research Institute, Garrett Engine, and the NDE Section at LLNL are combining resources and expertise to evaluate various NDE techniques. The goals are to accurately dimension the internal geometries and detect anomalies intrinsic to hollow cast blades. Results of this project will be used to plan future funding activities for development of advanced NDE techniques for turbine blade inspection. The complex geometry, high aspect ratio and material characteristics of the nickel alloy used in turbine blades, limits the nature of internal information obtainable from NDE imaging techniques such as radiography, infrared, and ultrasonics; and since CT is not limited by their shape it is a critical NDE technique for turbine blade evaluation. This inspection includes the detection of voids, cracks, inclusions and localized porosity, in addition to the dimensioning of wall thicknesses, inner core orientation and core integrity. We also seek to characterize the blade materials for dross, changes in crystal orientation, and possible changes in alloy composition. Inspections could be done for both new and aging blades. The characterization of the blade materials is a very difficult NDE problem.

A photograph of the different types of turbine blades examined in our CT studies is shown in Fig. 5. We have used the energy discriminating scanners to obtain 2D quantitative images and are using these data to help interpret non-energy discriminating 3D scan data sets. A representative 2D image of a single crystal turbine blade acquired using the MECAT scanner is shown in Fig. 6. This data reveals most of the external and internal details of the turbine blade with little CT imaging artifacts. Unfortunately, this data set takes several days to acquire and is at a lower than required spatial resolution (voxel size $0.5 \times 0.5 \times 1.0$ mm). A faster (hours) and higher spatial resolution (voxel size $0.1 \times 0.1 \times 0.1$ mm) medium energy, area-array detector CT (MDCAT) scanner under development was used to scan a turbine blade of the same type. This data was acquired at 250 kV and 2 mA. Representative 3D renderings of the resultant volume image data from this scanner are shown in Figure 7. This and other preliminary data suggests that the 3D data sets can help in the inspection of these blades. The material characterization problems as mentioned above are more difficult and are still under investigation. For example, we are incorporating the 2D and 3D data to better understand the characterization problem and are seeking other methods for the complete nonintrusive evaluation of single crystal turbine blades.

4. FUTURE ISSUES

Computed tomography is becoming a mature science, but there are still many issues to be studied. Indeed, each new application of CT to an inspection problem defines a new technical challenge to be overcome. One such problem, mentioned above, is that many aircraft structure have a shape with a high aspect ratio, thus causing difficulty of x-ray penetration in the long direction. Limited-data reconstruction algorithms have been applied, with some improvement, but further research is required in this area. We have also been experimenting with varying the data acquisition time, source energy, and current as a function of path length to change the transmitted flux at different angles of rotation to improve the measurement statistics in all directions. We have had good success with this method, but are still exploring other techniques for optimal CT scanner design.

A related problem is that of access to the component under inspection. Due to the geometry of many aircraft inspection problems, CT is inconvenient or dangerous. Since CT requires transmission of the x-rays at several angles about and through the part, limited-angle inspections are often necessitated by the flaw location. Laminographic and other limited-data CT measurements are often taken, and reconstruction methods are still under study for this type of problem.

Another area of active research is in the coupling of CT data to CAD databases. This is important for both part verification of fabrication and assembly, and for generation of new CAD models. We are continuing to explore new ways of improving this interaction.

5. SUMMARY

Computed tomography is a powerful tool for imaging the internal structure of aging aircraft parts. If performed correctly CT can provide fully 3D data sets which are dimensionally correct, and under certain circumstances quantitatively accurate. The applications shown here reveal that we can map the attenuation function of interior structure as well as localize and identify internal defects. It is important to note that we have shown only a small cross-section of the possibilities of CT. However, the difficulties of access, cost, and safety are also factors to consider in using CT for aircraft inspections.

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Fig. 1 The spatial resolution and energy range for which LLNL scanners are operational is depicted. The acronyms are called out in the text except for the segmented high purity germanium detector based scanner S-HPGe CAT and the linear array based scanner TCAT. These two scanners are under development.

Fig. 2 Parallel projection CT geometry in object space for a fixed slice plane along the z-axis.

Fig. 3 Representative images of the F-111 wing panel with corrosion. The CT cross-sectional slice (a) represents a cut through the panel as denoted by the black line in the radiograph (b). The gray scale under the CT image relates gray tones to the linear attenuation coefficient.

Fig. 4 Representative images of the aluminum airframe component. The CT cross-sectional slice (a) represents a cut through the part as denoted by the black line in the radiograph (b). The gray scale under the CT image relates gray tones to the linear attenuation coefficient.

Fig. 5 Photograph of some of the turbine blades used in our CT studies.

Fig. 6 Quantitative 2D CT image (voxel size $0.5 \times 0.5 \times 1.0$ mm) of a turbine blade acquired by the MECAT energy-discriminating CT scanner. The grey scale under the CT image is in cm^{-1} units. Additional quantitative information is shown in the two 1D-profiles plotted as a function of attenuation (cm^{-1}) versus distance along the lines labeled in the CT image.

Fig. 7 Representative 3D renderings of the resultant volume image data (voxel size $0.1 \times 0.1 \times 0.1$ mm) from the MDCAT scanner of a turbine blade. The different tones of gray are used as 3D perception and are not related to attenuation as in the 2D images.

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