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Computed Tomography*

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COMPUTED TOMOGRAPHY (CT) is an imaging technique that generates a three-dimensional (3-D) volumetric image of a testpiece. As the testpiece rotates, the CT system collects hundreds to thousands of radiographic projections that can later be used to reconstruct the 3-D volume of the testpiece (Fig. 1a). To perform the 3-D reconstruction, CT systems require a computing procedure to calculate, locate, and display the point-by-point relative attenuation of the energy beam passing through the testpiece.

Computed tomography has been demonstrated with a number of different types of energy beams, such as ultrasound, electrons, protons, α-particles, lasers, and microwaves. In industrial nondestructive evaluations (NDEs), however, only x-ray computed tomography (XCT) is considered to have widespread value. For this reason, XCT is also referred to as industrial CT (iCT). X-ray computed tomography collects and reconstructs the data of x-ray transmission through a two-dimensional (2-D) slice of an object to form a cross-sectional image without interference from overlying and underlying areas of the object. The CT image represents the point-by-point linear attenuation coefficients in the slice, which depend on the physical density of the material, the effective atomic number of the material, and the x-ray beam energy. The CT image is unobscured by other regions of the testpiece and is highly sensitive to small density differences (<1%) between structures. Computed tomography systems can also produce digital radiography (DR) images, and the DR and CT images can be further processed or analyzed within the computer. A series of CT slices (2-D) can be used to characterize the whole object volume (3-D), with the data reformatted to display alternate planes through the component or to present 3-D surfaces of structures within the object. Indeed, in recent years, thanks to the development of new technologies, regarding not only mechatronic but especially computer data-processing aspects, CT took a strong hold in the expanding field of nondestructive tests and dimensional metrology, because it is an ideal technique to carry out the defect analysis and the measurement of the outer as well as the inner geometry of a specimen without the need to cut it through (therefore preventing a complete nondestructive coordinate measurement). Thanks to CT, the whole 3-D volume of the specimen can now be reproduced compatibly with the dimensions and characteristics of the specimen

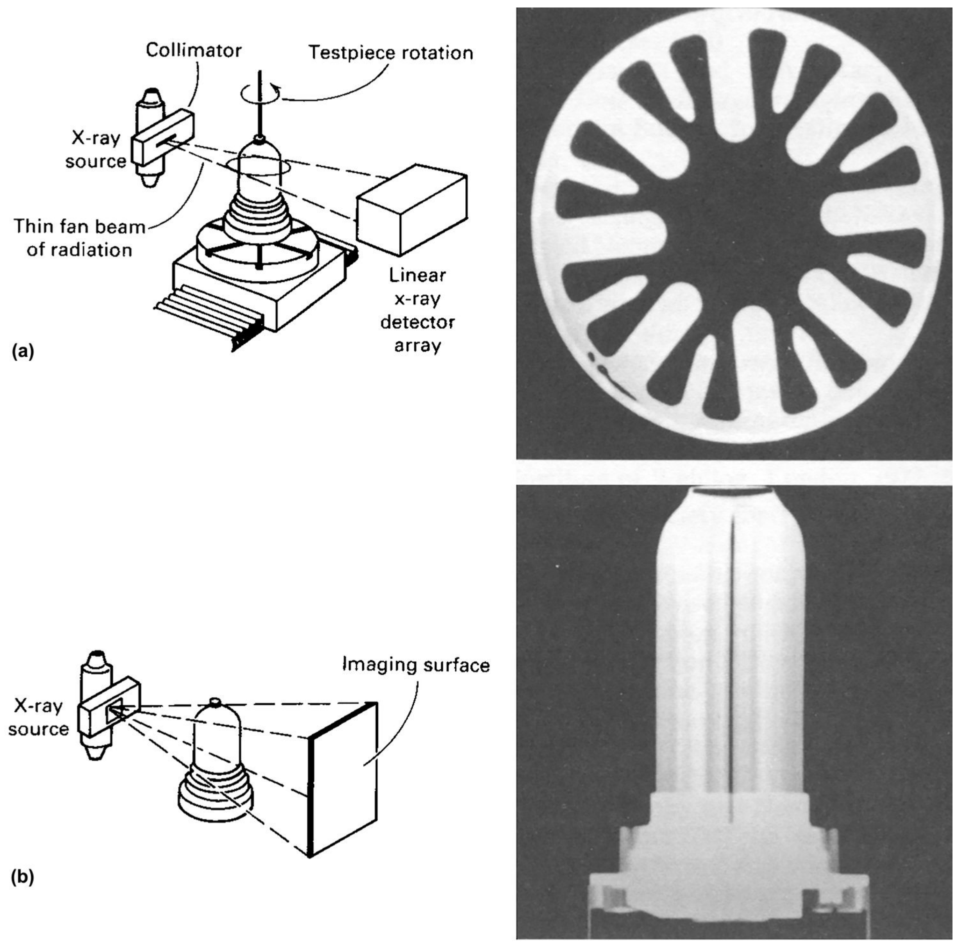


Fig. 1 Comparison of (a) computed tomography (CT) and (b) radiography. A high-quality digital radiograph (b) of a solid rocket motor igniter shows a serious flaw in a carefully oriented tangential shot. A CT image (a) at the height of the flaw shows the flaw in more detail and in a form an inexperienced viewer can readily recognize. Courtesy of J.H. Stanley, ARACOR

*Revised and updated from M.J. Dennis, Industrial Computed Tomography, *Nondestructive Evaluation and Quality Control*, Vol 17, *ASM Handbook*, ASM International, 1989, p 358–386 itself and with the suitability of the system. (Some large and high-absorbing components require special system architectures and parameters settings.) Moreover, CT allows one to work on a virtual 3-D model, allowing the separation between data-collection and data-processing steps, which can be performed in different time and locations.

Historical Background

The mathematical principle of CT was developed early in the previous century by Radon (Ref 1), but application of the technology occurred much later. Techniques were developed in the 1950s for radioastronomy (Ref 2), and experimental work progressed through the 1960s, primarily using nuclear tracer and electron microscopy data (Ref 3–5). In the late 1960s and early 1970s, Nobel Prize winner G. Hounsfield at EMI, Ltd., in England developed the first commercial XCT system, also known as a computerized assisted tomography scanner (Ref 6). Commercial CT scanners also found increased acceptance with the availability of inexpensive computing power, and industrial testing was considered an appropriate application in this early development of commercial CT systems. These early efforts, however, were directed primarily toward applications for medical diagnostic imaging. There was some limited use of CT in the 1970s for industrial and research applications; this work was primarily done on existing medical systems.

Since the end of the 1970s, dedicated efforts have been applied to the use of CT in industry. The petroleum industry was one of the early major users of medical-type scanners to analyze oil drilling core samples and to assist in analyzing secondary oil recovery methods in rock samples. Medical CT systems in hospitals and industry are also used to nondestructively test industrial components, primarily carbon composite materials and light metal alloy structures (Ref 7). Diagnostic medical scanners, however, are designed for a specific task. They provide high-quality images of the human body but are not suitable for large, dense objects.

Later, iCT systems began to be manufactured to address specific inspection objectives that extend beyond the capabilities of medical CT. Key differences include the ability to handle dense materials and larger objects, the use of higher-energy x-ray sources, the use of systems with higher resolution, and the ability to operate within the manufacturing environment. The U.S. military services have actively driven the development of dedicated industrial CT systems. In the late 1970s and early 1980s, several programs were initiated with specific inspection objectives. Early programs included systems for inspecting large rocket motors and systems for inspecting small precision castings in aircraft engines. Since these early systems, advancements have been made to extend the range of capabilities and applications.

In early 1990s, the first attempts to exploit CT systems in metrological analysis were performed, but the main drawback was the lack of accuracy ($\leq$0.1 mm, or 0.004 in.), which is one of the most important requirements in this type of evaluation, together with the traceability to the Système International d'Unités (SI) I unit of measurements. In the following decade, several technologic improvements occurred, leading to the design of the first dedicated metrological CT system, which was presented for the first time at the Control Fair in Stuttgart, Germany, in 2005. This type of machine finally allowed accuracy in the range of micrometers, and since that moment, several different CT systems for coordinate measurement have been designed and put on the market for industrial applications.

Because of the increasingly stringent performance and safety requirements in the aerospace, automotive, and transport industries, CT finds its largest market here. Other important applications concern electronics and microelectronics (e.g., printed circuit board inspection, Ref 8); emerging iCT markets are the food industry (e.g., inspection of the fat and bone content in certain meat cuts, or contaminant check within food packaging) and the industry of new materials (e.g., carbon-fiber-reinforced polymers, Ref 9). Another important field for CT applications is that of cultural heritage (e.g., fluid flow simulation and characterization of the pore network in limestone of historical buildings, Ref 10; inspection of bowed stringed instruments, Ref 11–13).

New computational power with modern computers allows, from a data-processing viewpoint, an almost completely automatic analysis that shows internal defects such as porosity, cracks, or wall thickness; computer-aided design (CAD) comparison (namely, the metrology comparison with the nominal CAD of the component); or the analysis of composite materials internal fiber, up to finite-element analysis simulation of tomographic volumes, taking into account internal defects of the testpiece (Fig. 2).

Basic Principles of Computed Tomography

The basic technique of CT is illustrated in Fig. 3. The testpiece is interrogated with a beam of radiation, which is attenuated as it passes through the testpiece. The fraction of the x-ray beam that is attenuated is directly related to the density and thickness of material through which the beam has traveled and to the composition of the material and the energy of the x-ray beam. Computed tomography uses this information, from many different angles, to determine the cross-sectional configuration with the aid of a computerized reconstruction algorithm. This reconstruction algorithm quantitatively determines the point-by-point mapping of the relative radiation attenuation coefficients from the set of 2-D radiation projections.

The CT scanning system contains a radiation source and radiation detector along with a precision manipulator to scan a testpiece from different angles. The x-ray detector is usually a flat panel detector consisting of a 2-D array of pixels. Compared to the straight or curved line detector arrays (LDAs), consisting of a one-dimensional (1-D) array of pixels that were more widely used in the past, the use of flat panel detectors is less time-consuming, because during the scanning a cone beam rather than a fan beam (collimated x-ray beam) and the registration of a 2-D projection can be used. In cases with particularly dense or thick workpieces or scattering problems, linear detectors still remain the most suitable. Indeed, LDAs provide better signal-to-noise ratio and resist higher x-ray energy.

In either case, the x-ray source is collimated to form a cone (or fan) beam that is wide enough to expose all of the detector elements (Fig. 1a). The data-acquisition system reads the signal from each individual detector element (pixel), converts these measurements to numeric values, and transfers the data to a computer to be processed. To obtain the full set of transmission data required to produce the CT image, the object, source, or detector

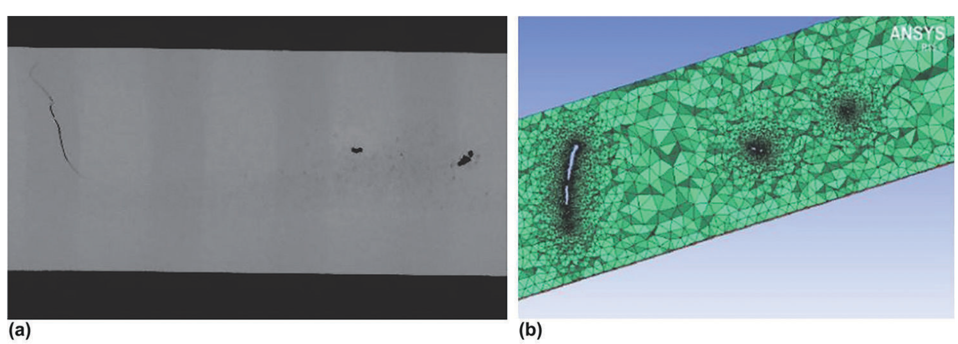


Fig. 2 (a) Computed tomography (CT) transversal section of an aluminum casting sample including a linear discontinuity and two voids. (b) Corresponding mesh obtained from the CT volume in order to perform a finite-element structure analysis

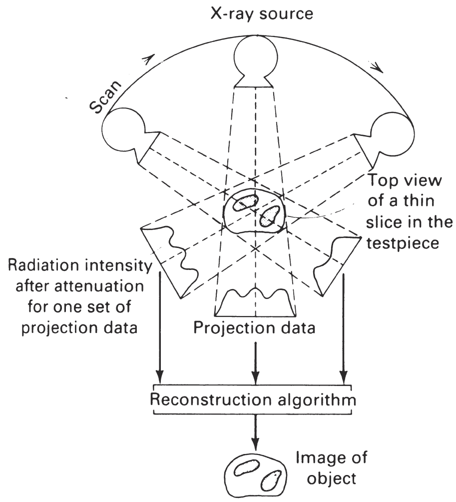


Fig. 3 Computed tomography process

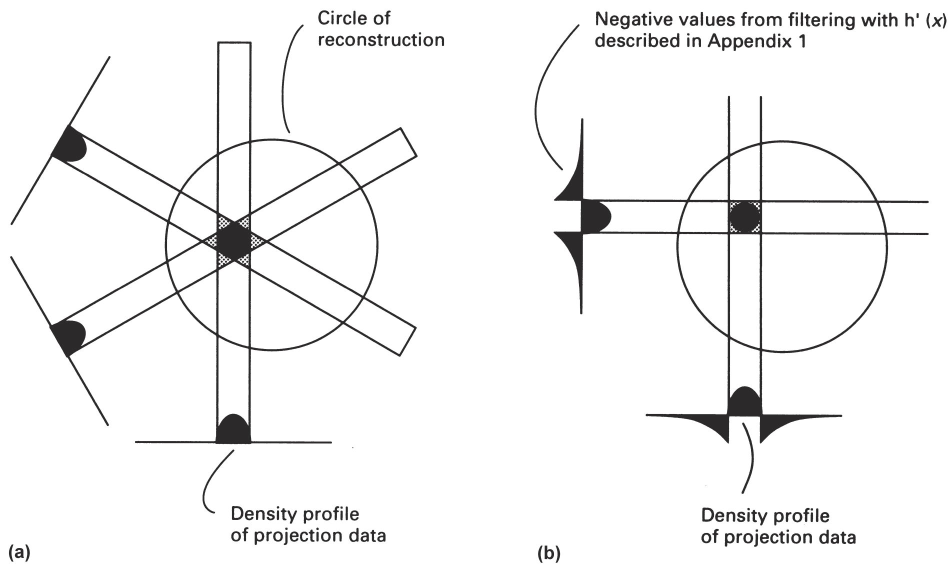


Fig. 4 Image reconstruction by (a) simple backproiection and (b) filtered backprojection. (a) Simple backprojection produces a blurred and broadened image. (b) Filtering can subtract the smear from other projections and reduce the broad blurring when backprojection is performed from many angles.

moves while a sequence of measurements is made. This motion may involve rotation of the test object relative to the source and the detector (Fig. 1a) or a combination of rotation and translation. The various types of scanning geometries are discussed in the section "Computed Tomography System Design and Equipment" in this article.

The CT image reconstruction algorithm generates a 3-D image from the set of 2-D radiation measurements taken at different scanning angles. The reconstruction algorithms used to generate the CT image fall into two groups: transform techniques and iterative techniques. The transform techniques are generally based on the theorem of Radon, which states that any 2-D distribution can be reconstructed from the infinite set of its line integrals through the distribution. (A line integral in CT is the sum of linear attenuation coefficients for one ray of radiation transmitted across the length of a cross-sectional slice.) The iterative techniques are generally algebraic methods that reconstruct the 2-D image by performing iterative corrections on an initial guess of what the image may look like. Iterative methods are rarely used, except when only limited data are available, because they require much more calculation time.

Some of the techniques used in CT image reconstruction are discussed in Appendix 1 in this article. The method most commonly used is the filtered (or convolution) backprojection technique. This technique filters (or convolutes) the projection data and then backprojects the filtered data into the 3-D image matrix. The backprojection process is the mathematical operation of mapping the 2-D projection data back into a 3-D grid, and it is equivalent to smearing the filtered projection data through the corresponding object space (Fig. 4b). The backprojected image values are calculated by taking each point in the image matrix and summing all filtered projection values that pass through that point. The sharpening filter is applied to the measured projection data to compensate for the blurring of the image that is a consequence of the backprojection process (Fig. 4a). Additional information on the basic concepts of reconstruction processing is presented in Appendix 1, along with references to more detailed descriptions of the mathematical reconstruction processes. A glossary of terms and definitions is provided in Appendix 2 in this article.

The CT Image. The CT reconstruction process yields a 3-D array of numbers corresponding to the 3-D volume of the testpiece. Each of these numbers is a pixel or picture element in the cross-sectional image (Fig. 5c). The reconstructed image is an array of many pixel values per image, and the arrays have sizes such as 512 × 512 × 512, 1024 × 1024 × 1024, or 2048 × 2048 × 2048 pixels. Because the scan transmission measurements are made with an x-ray beam of some thickness (Fig. 5a), pixel value in the 2-D image corresponds to a finite volume of the material in the object referred to as a voxel, or volume element (Fig. 5b).

The pixel values are usually an integer value that is proportional to the average linear x-ray attenuation coefficient of the material in the corresponding voxel. The linear attenuation coefficient is approximately proportional to the physical density of the material and is a function of the effective atomic number of the material and the spectral distribution of the x-ray beam. Because these pixel values are more or less proportional to the density of the material, they are sometimes referred to as density or x-ray density values. This is a

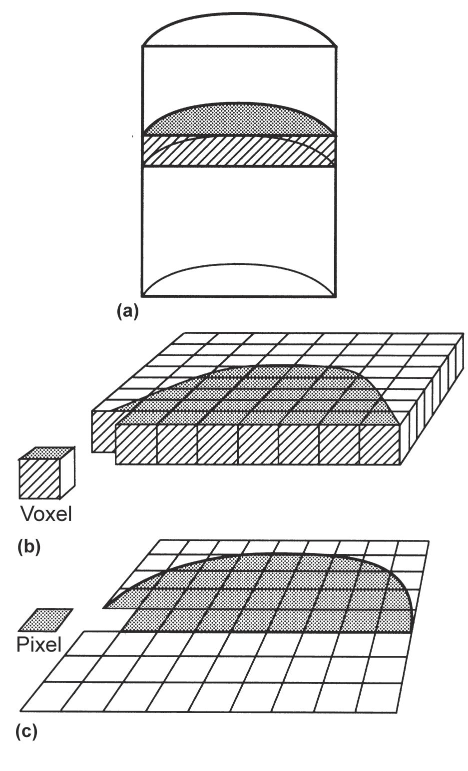


Fig. 5 Components of a computed tomography (CT) image. (a) The x-ray transmission measurements and resultant CT image correspond to a defined slice through the object. (b) The cross-sectional slice can be considered to contain a matrix of volume elements, or voxels. (c) The reconstructed CT image consists of a matrix of picture elements, or pixels, each having a numeric value proportional to the measured x-ray attenuation characteristics of the material in the corresponding voxel.

useful concept in interpreting images, but it is necessary to remember that other factors affect this value when objects contain multiple materials or when images obtained at different energies are compared.

The scaling of the linear attenuation coefficient into an integer pixel value, as well as the range of coefficients covered by the CT number scale, is somewhat arbitrary among systems. Medical systems use an offset scale that is normalized to water. These systems assign air a CT value of −1000, water is at 0, and a material twice as attenuative as water has a CT value of +1000. Industrial CT systems normally set the value for air at 0, but no standard scaling of the CT values is applicable to all the various materials and x-ray energies used.

To permit interpretation of the information in the reconstructed array of numbers, this information is displayed visually as an image. Human perception is limited, however, and cannot distinguish the many thousands of density levels that may be present in a single image. For distinguishing small density differences over a wide range of densities, the display system uses an interactive CT number windowing capability. This display windowing presents a limited range of CT numbers over the full grayscale range of the visual display and is a powerful tool in analyzing subtle features in the image data. Color can also be used to enhance the displayed image, where ranges of CT numbers are presented as a particular color. The color scales can be set up as a rainbow of colors, as hues of a particular color, or as a hot body spectrum.

Types of CT Systems and Applications

Several types of CT systems exist, suitably designed according to their specific applications, which can be divided into three main areas: clinical, materials analysis and flaw detection, and dimensional metrology. Each of them is characterized by specific requirements, and therefore, the technical features of the CT system must vary accordingly. Materials analysis, flaw detection, and dimensional metrology are performed by iCT devices, which allow dimensional quality control and material quality control to be performed simultaneously. As mentioned previously, CT devices were first produced for clinical applications; in 2005, CT devices for dimensional metrology were put on the market. This is not fortuitous, because the latter must meet higher requirements in terms of accuracy and spatial resolution and moreover require more powerful sources and advanced technologies to inspect large objects and materials with high atomic numbers.

In clinical CT, which can be considered the precursor of iCT, the patient remains generally stationary, or at least is slowly translated, while the source and the detector are continuously rotated around him, with a horizontal rotation axis. To safeguard patient health, radiation doses must not exceed the safety limits. Moreover, in clinical CT, accuracy requirements are not as stringent as in industrial applications.

Industrial CT applications are distinguished into materials analysis and dimensional metrology. Modern systems can simultaneously perform both. In materials analysis, CT is exploited as an NDE for flaw detections, porosity check, and other materials evaluations such as density measurements. In dimensional metrology, CT is the only NDE technique that allows reproduction of the entire inner and outer geometry of the component in a virtual 3-D model without the need to cut the real component through. This feature is particularly advantageous in case of quality control of workpieces with a complex structure or inaccessible inner parts, such as workpieces produced by additive manufacturing or in case of multimaterial assemblies. In an iCT system, the object is generally rotated without translation movement, while the source and the detector are kept stationary or moved vertically and horizontally. For certain applications, the relative position of specimen, source, and detector can be varied to obtain the best spatial resolution. Radiation doses are not a critical matter for most of the workpieces to be analyzed, and all the systems must be fitted with proper radiation shielding for the safety of operators. In iCT, the size of the object to be analyzed can vary considerably (from millimeters to even meters); hence, the architecture of the machine should be properly designed according to the particular application. The principal issue concerning the scanning of large components is that larger detectors and powerful sources are needed to increase the maximum penetrable thickness within the object material. Therefore, equipment ranges from large-scale CT devices, equipped with high-voltage x-ray tubes (up to 600 to 800 kV tubes) or even with linear accelerator x-ray sources, to small devices designed for scanning electron microscope and transmission electron microscope applications. Unlike clinical applications, sometimes in iCT the specimen may not be easily accessible, preventing the complete 360° rotation required by traditional CT, thus invalidating the classical geometry of iCT systems characterized by the rotation of the object and by the motionless of the source and the detector. In this case and in cases of large flat objects, which present a very high absorption in at least one direction, digital laminography, also referred to as digital tomosynthesis, can be performed. In this technique, the source and the detector are moved simultaneously around a focal point located in a plane of interest in the component. Only the plain of interest remains in focus, while all the planes above and below it are blurred. Laminography can be used to perform analysis of printed circuit boards. When used for dimensional metrology, the CT system must fulfill special requirements regarding accuracy, spatial resolution, and measurement traceability. Therefore, system stability is extremely important for this type of task, and one of the parameters that must be kept under control to improve accuracy is temperature. The thermal stability of the system can be accomplished by cooling both source and detector. Because of the high performances required, iCT systems for dimensional metrology should comply with standard procedures and guidelines, the most used of which is the German guideline VDI/VDE 2630 part 1.3, because an International Organization for Standardization (ISO) standard for CT metrology is not yet available.

Industrial CT characterized by a spatial resolution below 100 μm is called micro-CT. This performance was initially achieved only by synchrotron-based systems, but now, because of technological improvements, it can be obtained with tube-based systems as well. The most advanced tube-based micro-CT systems available on the market can even reach a spatial resolution of 0.5 μm. Summarizing, compared to clinical CT, which is devoted to the analysis of living tissues, industrial CT shows the following great improvements in terms of accuracy and spatial resolutions:

- Focal spot size can be lowered to a few micrometers, with great advantages to the image quality.
- Because a material object and not a person is being examined, the exposure time can be increased to obtain adequate photo count.
- The relative position of specimen, source, and detector are not fixed and can be varied to improve spatial resolution.

With the better technical performance afforded by using industrial micro-CT, 3-D surfaces can be extracted, analyzed, and saved with a resolution on the order of the micrometers.

Capabilities

X-ray CT is a radiological procedure and has many of the same considerations as film and real-time radiography. The system must be designed to permit sufficient penetration of the x-rays through the object. Radiation shielding is required as part of the system or installation. Immersion is not required, and air gaps, multiple materials, complex shapes, and surface irregularities do not present a significant difficulty. The displayed parameter corresponds to the linear attenuation coefficient of the materials within the test specimen, and structures differing by a fraction of a percent can be visualized. In a CT image, the structures of interest are not obscured by other structures, and the sensitivity and ability to detect a feature are less dependent on the presence and overall thickness of other structures.

Because the CT image corresponds to a stack of thin sections through the object, features can be localized in three dimensions. This can be highly valuable in determining whether a flaw is within a critical area and in providing specific information on the reparability of a component and how the repair should be implemented. This spatial information also permits one to make certain dimensional measurements from the image that may otherwise be difficult or impossible to obtain nondestructively. The ability to provide spatially specific structure and density information also opens up the opportunity to obtain 3-D data representations of physical components for CAD documentation and computer-aided engineering analysis.

Computed tomography also has its limitations. Producing high-quality images requires a stable radiation source, a precise mechanical manipulator, a sensitive and highly linear x-ray detector system, considerable computing power (usually with high-speed array processors and dedicated graphics processing unit), and a high-quality image display. Consequently, the capital costs for industrial CT systems tend to be well above those of most routine inspection systems.

The fact that the CT image corresponds to a stack of thin sections through the testpiece provides beneficial information and sensitivity. This can produce throughput difficulties, however, if information is required over a large volume. Thousands of CT slices are required for fully characterizing an entire component. Typically, full-volume CT scanning is limited to certain low-volume, high-value testpieces or to the engineering evaluation of prototype or test specimens. In higher-volume production, CT images are often taken at specific critical positions for flaw detection or dimensional analysis. The digital radiography mode of these systems or some other conventional inspection technique is often used to identify suspicious indications, and CT imaging is used to characterize the structure or flaw to provide more information for the accept/reject/repair decision on the component. In higher-volume production, CT scanning can also be used with an automated process scan and semiautomatic or automatic postprocessing analysis through a purpose system.

Another limitation of industrial CT does not pertain to its ability to provide specific information but to the relative newness of the technology and the ability to obtain and use CT information. Critical inspections are normally defined as part of a component design, and prior designs did not consider the potential of CT. Inspection requirements can be changed but must be done on a component-by-component basis. This has limited much of the use of CT for existing components to in-process inspection for process control and minimizing scrap costs or to providing improved information for materials-review decisions.

Some of the current component designs require CT inspection to ensure reliability, to reduce the assumed maximum contained defect used in the design, or to design structures that do not provide good access for ultrasonic or routine radiographic inspection. This ability to characterize the interior structures of complex shapes and assemblies reduces the constraints for inspectability and therefore provides design engineers with the freedom to design. (Additive manufacturing is a perfect example of that.)

Detection Capabilities. The ability to present a density (or linear attenuation coefficient) map across a slice through a specimen allows the visualization of many types of structures and flaws. The ability of CT to display specific features will vary with the capabilities of the specific system and the operating parameters used to obtain the image. Assuming adequate capabilities for a particular scanning situation, some generalizations can be made regarding the suitability of CT for various flaw types:

- Voids and inclusions are readily detectable high-contrast targets. Targets considerably smaller than the resolution of the system can be seen but will have less contrast from the background material. On the other hand, high-structure noise, as in composites, can further limit the detectability of small voids or inclusions.
- Porosity and microshrink reduce the density of the material and are usually visible if distributed over a multipixel area. The percentage of porosity can be quantified with manual or semiautomatic properly controlled procedures.
- Relative density measurements for a material or for materials with the same effective atomic number can be made. Absolute density can be obtained with properly controlled procedures. Alternative techniques, such as dual-energy scanning, may improve capabilities with multiple materials.
- Separated or displaced cracks are detectable. As with voids, the separation may be well below the resolution of the system, but contrast will drop as the separation decreases. Detectability may be affected by structure noise or if the crack is adjacent to a high-contrast boundary.
- Disbonds and delaminations are detectable if separated. They are similar to cracks, with the additional complication of adjacent structures with the same orientation.
- Residual core material in castings is readily seen in bulk. Thin surface layers can be difficult to detect.
- Machining defects, such as overdrills and scarfing grooves, are readily seen. Computed tomography can assist in quantifying the extent of machining defects.

Comparison to Other NDE Methods

X-ray CT provides one method of detecting and locating the internal flaws of a testpiece. Other common NDE methods of internal flaw detection and location include radiography and ultrasound, which are compared with XCT in Table 1. Less common methods in industrial testing are nuclear tracer imaging, nuclear magnetic resonance imaging, and x-ray backscatter imaging. Acoustic emission, holography, and other techniques provide indirect or bulk information on the internal structure without specifically defining the structure.

Computed Tomography and Radiography. X-ray CT is a radiological technique and has many of the same benefits and limitations as film and real-time radiography. The primary difference is the nature of the radiological image. Radiography compresses the structural information from a 3-D volume into

Table 1 Comparison of ultrasound, radiography, and x-ray computed tomography

Performance characteristic	Ultrasound	Radiography	Computed tomography
Parameter imaged	Acoustic impedance differences, attenuation, velocity	Attenuation	Attenuation
Handling	Immersion, squirter	Flexible	Scanner size limitation
Surface roughness	Poor	Fair	Good
Complex structures	Poor	Fair	Good
Limitations	Needs acoustic coupling; not suitable for acoustically noisy materials	Penetration one side	Penetration over a 360° scan; limited volume imaged per scan
System costs	Medium	Medium	High
Flaw detection			
Voids	Good	Good	Good
Inclusions	Good	Fair	Good
Porosity and microshrink	Good	Fair	Good
Density variations	Fair	Fair	Good
Cracks	Good (not aligned)	Fair (separated and aligned)	Fair (separated)

a 2-D image. This is useful in that it allows a relatively large volume to be interrogated and represented in a single image. This compression, however, limits the information and reduces the sensitivity to small variations. Radiographic images can be difficult to interpret because of shadows from overlying and underlying structures superimposed on the features of interest. Further, a single radiographic image does not provide sufficient information to localize a feature in three dimensions. Some of the performance characteristics of radiography and CT are compared in Table 2.

Nuclear Tracer Imaging. Both nuclear imaging and magnetic resonance imaging are widely used for medical diagnostic imaging but are infrequently used for industrial structural imaging. Nuclear tracer imaging yields an image of the distribution of a radioactive substance within an object. It has the potential for imaging flow paths through a structure or for the absorption of the tracer in open, porous areas of the object. Tracer studies obviously require the capability to handle unsealed radioactive materials, and the images are affected by the attenuating structure of the object between the tracer and the detector. Nuclear tracer imaging comprises two different advanced CT techniques that are similar to XCT. These are single-photon emission computed tomography (SPECT) and positron emission tomography (PET) scanning, which produce cross-sectional displays of the tracer concentration (Ref 15).

Nuclear magnetic resonance (NMR) imaging, or magnetic resonance imaging, is similar to XCT in the type of images produced and in some of the methods for processing the NMR data. For NMR imaging, the object is placed in a strong magnetic field. The magnetic dipole of certain nuclei, such as hydrogen, will tend to line up with the magnetic field. These nuclei will precess, or rotate, at a particular frequency that is dependent on the nuclide and the magnetic field strength. Adding energy in the form of radio waves at this specific resonance frequency will cause the nucleus to be pushed out of alignment with the magnetic field. The nucleus, after some short period of time, will then fall back into alignment with the magnetic field and emit a radio wave in the process. The emitted radio waves are monitored, the time constants measured, and the magnetic fields varied in order to produce cross-sectional images of the particular nuclide being monitored.

Nuclear magnetic resonance imaging has been highly successful for the diagnostic medical imaging of the water-based human body but has severe limitations for most industrial imaging requirements. Nuclear magnetic resonance is sensitive only to nuclides with a nuclear dipole moment, that is, nuclei with an odd number of protons or neutrons. The nuclide of interest is generally required to be in a liquid or gelatinous state, because the time constants for solids are too short. In addition, the object cannot contain ferromagnetic materials, which would disrupt the uniform magnetic field, nor can it contain highly conductive materials that would interfere with the transmission of the radio waves. This technique has appeared useful for analyzing fluids in rock samples for the petroleum industry (Ref 16, 17). Some limited work has been demonstrated for industrial testing in which a liquid tracer, such as alcohol, was used to image the porosity within carbon composite structures (Ref 18, 19).

Backscatter or Compton imaging is a technique in which the object is irradiated by a narrow x-ray beam, and the Compton scattering of this radiation by the object is monitored (Ref 20). The amount of scattered radiation produced is directly related to the electron density of the material, which corresponds well to the physical density of the material.

The proportion of the x-ray beam scattered in a small volume of the object tends to be relatively small, and the x-rays are scattered in all directions. A portion of this scattered radiation is measured by detectors typically placed near the entry point of the x-ray beam.

In general, radiography or CT is preferred for internal inspection where it is practical to use. The major advantage offered by backscatter imaging is that it can be implemented from one side of the object. Other x-ray imaging methods require the source on one side of the object and the film or detector on the opposite side in order to measure x-ray transmission. Backscatter imaging provides a means of obtaining near-subsurface information, particularly if the object is very massive, does not permit x-ray transmission through it, or does not permit access to the opposite side (Ref 21, 22). Like CT, backscatter imaging can also generate images of planar sections through the testpiece.

Table 2 Comparison of performance characteristics for film radiography, real-time radiography, and x-ray computed tomography

Digital radiographic imaging performance with discrete element detector arrays is comparable to computed tomography performance values.

Performance characteristic	Film radiography	Real-time radiography(a)	Computed tomography
Spatial resolution(b)	>5 line pairs/mm	~2.5 line pairs/mm	0.2–4.5 line pairs/mm
Absorption efficiencies, %			
Absorption efficiency (80 keV)	5	20	99
Absorption efficiency (420 keV)	2	8	95
Absorption efficiency (2 MeV)	0.5	2	80
Sources of noise	Scatter, poor photon statistics	Scatter, poor photon statistics	Minimal scatter
Dynamic range	200–1000	500–2000	Up to 1×10^6
Digital image processing	Poor; requires film scanner	Moderate to good; typically 8-bit data	Excellent; typically 16-bit data
Dimensioning capability	Moderate; affected by structure visibility and variable radiographic magnification	Moderate to poor; affected by structure visibility, resolution, variable radiographic magnification, and optical distortions	Excellent; affected by resolution, enhanced by low contrast detectability

(a) General characteristics of real-time radiography with fluorescent screen-TV camera system or an image intensifier. (b) Can be improved with microfocus x-ray source and geometric magnification

Industrial CT Applications

Computed tomography provides a unique means of obtaining very specific information on the interior structure of components. Computed tomography technology is very versatile and is not restricted by the shape or composition of the object being inspected. Also, CT systems can be configured to inspect objects of greatly varying sizes, weights, and densities. Generally, systems designed to accommodate large objects do not provide spatial resolution as high as systems designed for the inspection of smaller objects.

The major limitations of CT are the relatively high equipment costs and the limited throughput for evaluating large volumes. Typically, full-volume CT scanning is limited to certain low-volume, high-value components or to the engineering evaluation of prototype or test specimens. In higher-volume production, CT images are often taken at specific critical positions for flaw detection or dimensional analysis. The digital radiography mode of CT systems (see the section "Special Features" in this article) or some other conventional inspection technique is often used to identify suspicious indications. The CT imaging mode is then used to characterize the structure or flaw to provide more information for the accept/reject/repair decision on the component.

The petroleum industry uses CT for geological analysis and for fluid dynamics research studies (Ref 23–29). Rock core samples are obtained from drilling sites to evaluate the oil production capabilities of a well. Computed tomography can be used to help evaluate these core samples with regard to heterogeneity, fracturing, or contamination by the drilling process. Small plugs are often taken from these core samples for extensive analysis of porosity, permeability, oil content, and other parameters. The CT data can assist in locating appropriate areas for these plug samples and in avoiding nonrepresentative samples and erroneous results.

Computed tomography is also used in dynamic flow studies of oil well core samples. The improved understanding of oil flow through the rock and the use of water, carbon dioxide, surfactants, and other chemicals to push the oil to a production well can have significant economic benefits. The test core samples are placed in sealed containers with the appropriate plumbing, and the flow experiments can be conducted at high pressures and elevated temperatures to simulate reservoir conditions.

The flow rates are typically slow, and a study can last many hours. A series of CT projections is obtained at various times in the study to characterize the fluid position. To distinguish the various fluids, contrast media or highly attenuating dopants, such as iodine, can be added to one of the fluids. The resulting data are processed to determine the percentage of saturation or volume concentration of the various fluids and gases present (Fig. 6). Dual-energy imaging is sometimes used to assist in quantifying these fluid concentrations. Dual-energy imaging uses CT scans of a section acquired at different x-ray energies to evaluate the effective atomic number of the materials present.

Another research example in the energy industry was a study funded by the U.S. Department of Energy on the process of burning coal (Ref 30). In this study, a controlled furnace was placed in a medical CT system. The thermal fronts and relative density changes were imaged by CT while the effluent gases and other parameters were monitored.

Composite structures, by their nature, are complex materials that can pose challenges in design, fabrication, and inspection. Because of the high strength-to-weight ratio of these materials, composite usage is increasing, especially in the weight-sensitive aerospace industry. Computed tomography imaging has found considerable use in assisting the engineering development, problem solving, and production of composite components (particularly carbon composite components). The ability to track the integrity of individual components can greatly simplify process analysis relative to a sampled destructive study.

Computed tomography has been used to evaluate the fabrication process for certain composite components, including molded chopped-fiber components, as shown in Fig. 7. Resin flow patterns (Fig. 7) can be seen, and an individual component can be evaluated at different stages of curing to determine the point at which processing defects are created in the component. Resin flows in composite materials are generally visible, assuming a difference in the linear attenuation coefficient between the fiber and resin material. Low-density resin flows with widths near the image resolution may appear similar to a crack with subresolution separation. The use of dual-energy techniques may help in distinguishing between similar indications. Fiber orientation in composite materials is sometimes seen, especially with chopped-fiber molded components. The ability to discriminate individual fiber bundles is highly dependent on fiber bundle size and system resolution. Computed tomography can detect indications of waviness in composite layers and porpoising (out-of-plane waviness). Radiographic tracer fibers appear with very high contrast.

Operational tests and tests to failure can also benefit from detailed data obtained at various stages of the test. One example of this type of use is the evaluation of rocket motor nozzles before and after firing tests (Ref 31). In this case, the degree and depth of charring were evaluated and compared with theoretical models. Computed tomography has been used in a number of situations to assist in the evaluation of valuable prototype components.

Some of the highest interest in the use of new techniques occurs with engineering problem solving. An example is the failure of the space-shuttle-launched communication satellites to obtain proper orbit in February 1984. In this case, CT demonstrated interlaminar density variations (Fig. 8b) in some of the rocket motor exit cones of the type used with the satellites. These variations had not been detected by routine inspection of the components. Computed tomography provided a mechanism to evaluate the existing inventories, permitting judgments to be made on the flight-worthiness of the remaining hardware (Ref 32).

Computed tomography is also used in the production inspection of certain composite hardware. This is particularly true in the case of composite rocket motor hardware because of the experiences discussed previously and the active role governmental agencies have played in driving this capability. The increased use of composite materials in critical structures is increasing the role of CT in the production inspection of composite components.

Rocket Motors. In addition to individual rocket motor composite components, CT systems are used to scan full rocket motors. Some of these systems use linear accelerator x-ray sources up to 25 MV and are designed to inspect solid propellant rockets in excess of 3 m (9.8 ft) in diameter. These systems can be used to evaluate the assembly of the various motor components and to evaluate the integrity and fit of the casing, liners, and propellant (Ref 33, 34).

Precision Castings and Forgings. Computed tomography systems are used for the production inspection of small, complex precision castings and forgings, especially turbine blades and vanes used in aircraft engines and liquid propellant rocket motor pumps. The

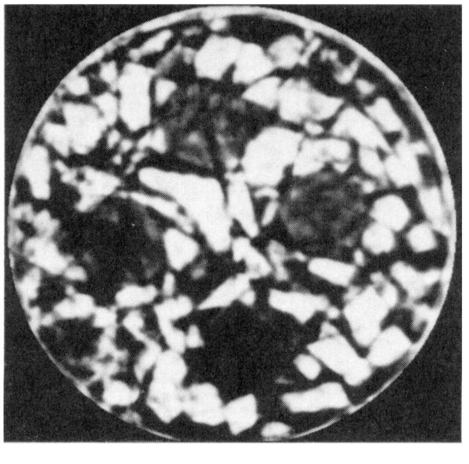


Fig. 6 Computed tomography image of a rock sample with oil and water. The lighter circular areas at the top and right are areas containing water, while the darker regions at the bottom and left are areas with oil. Courtesy of B.G. Isaacson, Bio-Imaging Research, Inc.

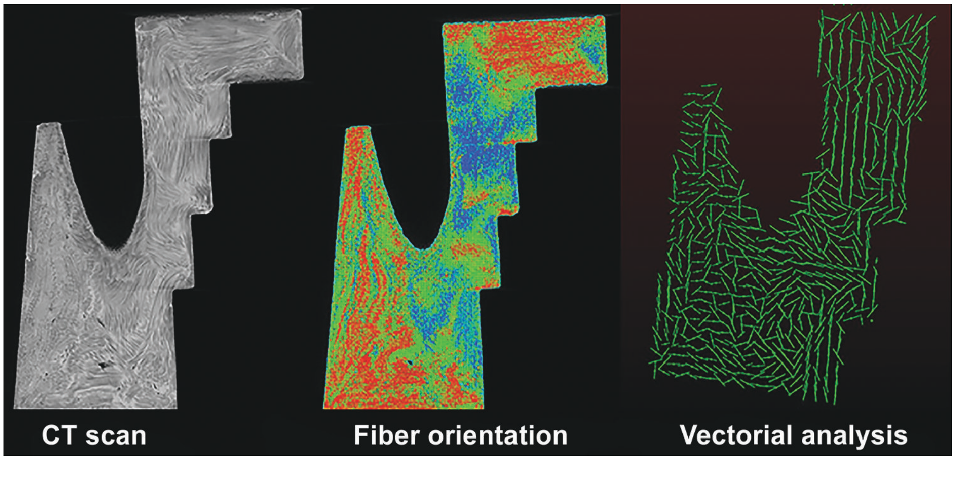
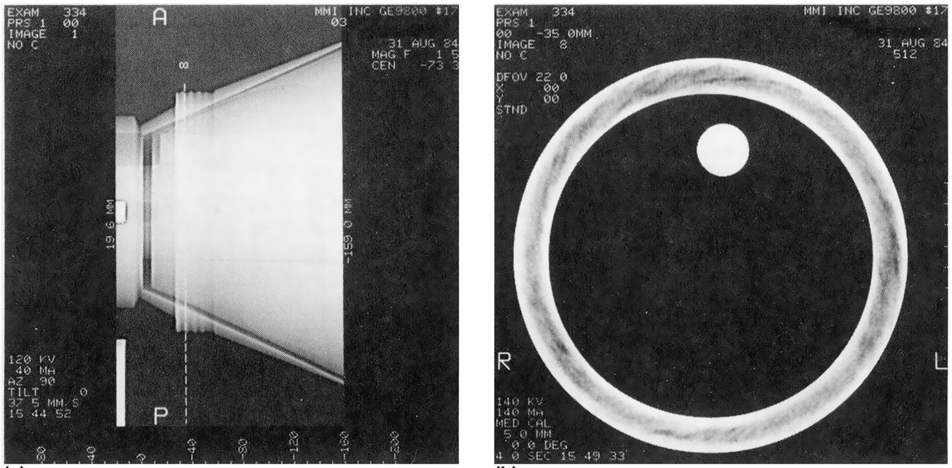


Fig. 7 Computed tomography image of a molded chopped-fiber carbon composite showing a resin flow (left) and a void in the center rib



(a) (b)

Fig. 8 (a) Digital radiograph of rocket exit cone showing the position for computed tomography scanning through the thread portion of the component. (b) Computed tomography image through threaded area of rocket exit cone. Computed tomography revealed the extent of interply density variations.

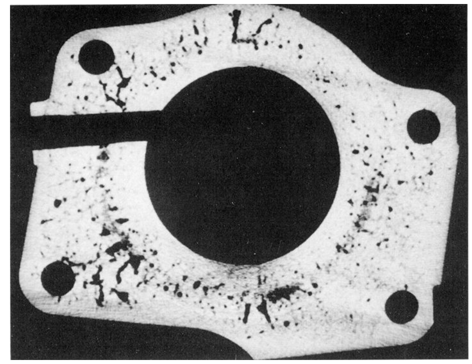


Fig. 9 Computed tomography image of cast housing showing severe shrinkage and porosity

ability to localize material flaws and passage dimensions has also permitted the reworking of complex castings and fabrications. In the aircraft engine industry, CT is considered an enabling technology that will allow large, complex structural castings to replace fabricated components, reducing both component weight and manufacturing costs. Computed tomography is also used to analyze the wall thickness of certain used blades to evaluate if sufficient material remains for refurbishing the component. This has permitted the overhaul and reuse of components that would otherwise be questionable.

Flaw Detection. Because of throughput considerations for production, casting flaws are generally detected in the digital radiography mode (see the section "Special Features" in this article for a discussion of the digital radiography mode). Computed tomography is used to detect flaws in critical areas and to further evaluate flaw indications detected by digital radiography or other methods (Ref 34–36).

Furthermore, iCT is used to detect flaws in casting prototypes or in a preproduction series. The specific data provided by CT for the evaluation of flaw indications allow for a more informed accept/reject decision. Porosity and microshrink reduce the density of the material and are usually visible if distributed over a multipixel area (Fig. 9). The percentage of porosity can be quantified with properly controlled procedures. Other detectable conditions include casting bridges or fins, residual core material in the casting (Fig. 10a), and machining defects (Fig. 10b).

Dimensional Measurements. Because of the density sensitivity of the CT data and the averaging of the density values within a measured voxel, dimensional measurements can be made with better precision than the resolution of the image. The use of CT for wall thickness gaging has advantages over other gaging techniques in that the measurements are not operator dependent, and precise information can be obtained from regions with internal walls and sharp curvatures.

Figure 11 shows a typical CT image of a turbine blade with the measured wall thickness information displayed. In this case, the wall thicknesses were measured with automated software, which makes many measurements along each wall segment (between ribs), marks the location of the thinnest portion, and posts the measured data in a table. The quantitative data can also be passed to a statistical software package for process control analysis. Applications are being pursued for using this dimensional information for subsequent machining operations, such as adjusting power levels for laser drilling. The ability to provide spatially specific structure and density information also opens up the opportunity to obtain 3-D data representations (Fig. 12) of physical components for CAD documentation and computer-aided engineering analysis.

Engineering Ceramics and Powder Metallurgy Products. The sensitivity of CT to density differences of a fraction of 1% can be applied to a number of materials characterization problems. Materials that vary in density or composition because of the fabrication process may benefit from this capability. Injection-molded powder metal components have been scanned with the potential of better density characterization and process control in the green state to produce an improved sintered product. The CT of advanced ceramic materials is also increasing, especially for high-stress and complex-shaped components (Ref 19, 37).

Assembled Structures. In general, the advantages of CT over alternative inspection methods increase with the complexity of the structure. The ability of CT to image the components in an assembly does not reduce the need for component inspection prior to assembly. This ability can be a valuable tool, however, when quality questions arise regarding the assembled product. Computed tomography can also be used to verify proper assembly or help evaluate damage or distortion in components caused by the fabrication process.

Examples and potential applications for CT cover a wide range. They include the evaluation of composite spars in helicopter rotor blades, detonators and arming devices, thermal batteries, and a variety of electronic assemblies. The major limitation is the capacity of the system and economic considerations, especially for large-production-volume items. Computed tomography can provide worthwhile capabilities even for low-cost, high-volume components by assisting engineering development and problem solving.

Bowed Stringed Instruments. During the last 30 years, CT has found an increasing importance in the diagnostic and metrology analysis of bowed stringed instruments. Indeed, violin makers are mostly interested in collecting information to be exploited in making and restoring instruments, and museums, dealers, and collectors want to obtain reports that should document the conditions of their precious collections in terms of worm damage and repairs, as well as more detailed information about the particular style of a violin craftsman. By means of micro-CT, wood patches, hide glue drips, and growth rings can be easily recognized. Therefore, CT represents an important tool for wood dating, because the information about growth rings position and dimension patterns allows one to perform dendrochronology, which, up to now, has been intensively used for dating instruments. Besides diagnostics, micro-CT also can be successfully exploited for reverse engineering applications, such as plate thickness mapping, curvature profiles, f-holes position, and wood density evaluation (Fig. 13, 14). With respect to other measurement systems, such as the coordinate-measuring machine (CMM) and laser and structured light scanners

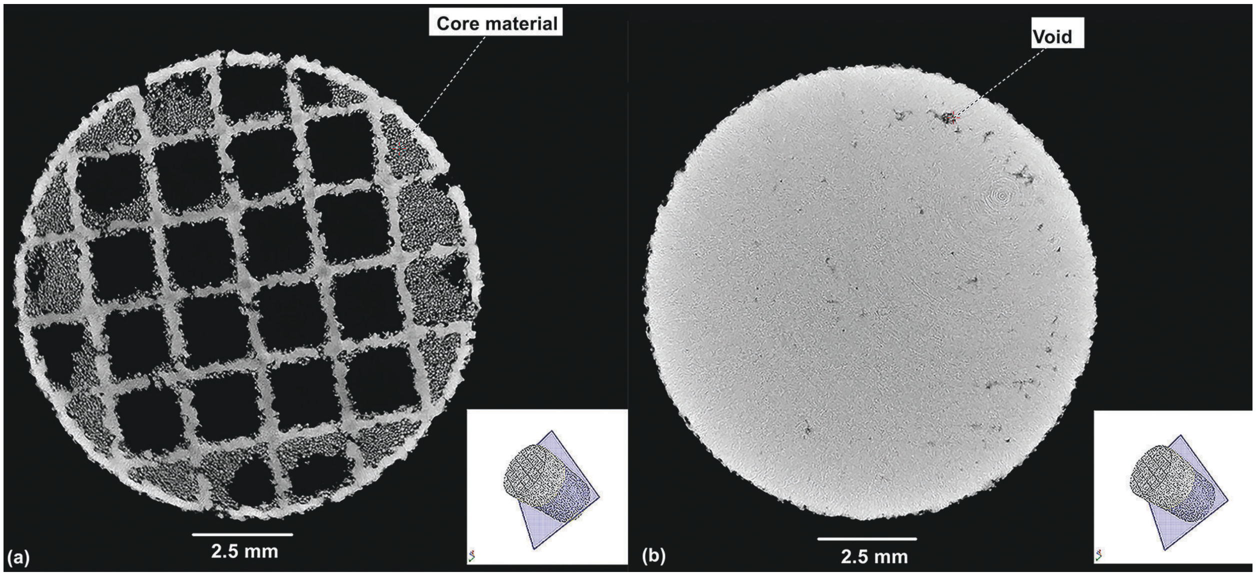


Fig. 10 Computed tomography images of an additive manufacturing sample with residual core material and voids.

Fig. 11 Cross-sectional computed tomography image through a turbine blade with wall thickness measurement locations and values determined with automated software

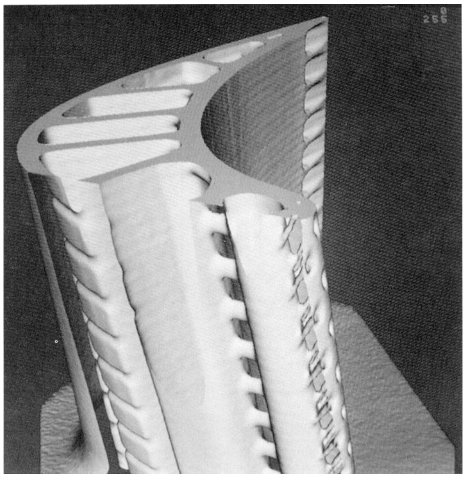


Fig. 12 Three-dimensional surface image of a turbine blade generated from computed tomography data

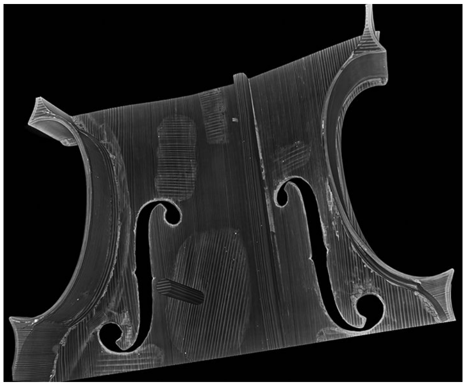


Fig. 13 Three-dimensional rendering of a violin top plate

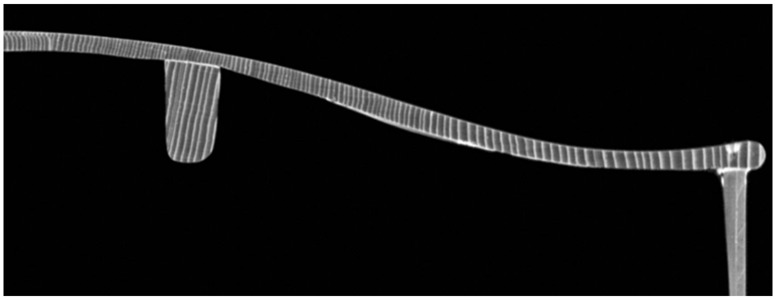


Fig. 14 Details of an axial section of the violin in Fig. 13

(LS), CT presents several advantages for this type of application. In fact, although the accuracy of tactile CMMs is proven and indisputable, and moreover, its application rests upon internationally accepted standards, its main drawback lies in the traditional shape and conformation of this type of free-form handmade instruments, because they all present a lot of curvatures and inaccessible features. Moreover, tactile CMM application carries the risk of damaging the instrument, and a noncontact system, such as CT or LS, is therefore preferable. If compared to LS, CT provides better results in terms of deviation from CMM reference measurements and uncertainty, and it has no problem in dealing with dark and shiny surfaces (as violin surfaces are).

Computed Tomography System Design and Equipment

Computed tomography systems are relatively complex compared to some of the other NDE imaging systems. The production of high-quality CT images requires a stable radiation source, a precise mechanical manipulator, a sensitive x-ray detector system with high accuracy and a wide dynamic range, considerable computing power (usually with high-speed array processors), and radiation shielding for personnel safety. Consequently, the capital costs for industrial CT systems tend to be well above those of most routine inspection systems.

The basic functional block diagram of an XCT system is illustrated in Fig. 15. The major components include:

- A precision mechanical manipulator for scanning the testpiece with a radiation source and detector flat panel and/or linear array. Several different scanning geometries are used to acquire the ordered set of transmission data (see the section "Computed Tomography Scanning Geometries" in this article). The mechanical subsystem may also include automated parts handling for loading and unloading the inspection station (Fig. 16).
- Radiation shielding for the safe use of the radiation source. The high-energy radiation sources used in industrial CT systems are typically shielded by placing the radiation source detectors in a room with shielded walls. Self-contained, shielded cabinet systems (Fig. 16) are often used for industrial systems with x-ray sources operating below 500 kV.
- A radiation source, such as an isotopic gamma source, an x-ray system, or a linear accelerator. The radiation sources used in industrial CT systems are similar to the x-ray and γ-ray sources used in industrial radiography.
- Flat panel detector for measuring the transmitted radiation. Industrial CT systems primarily use either gas ionization detectors or scintillation detectors; the latter are the most used.

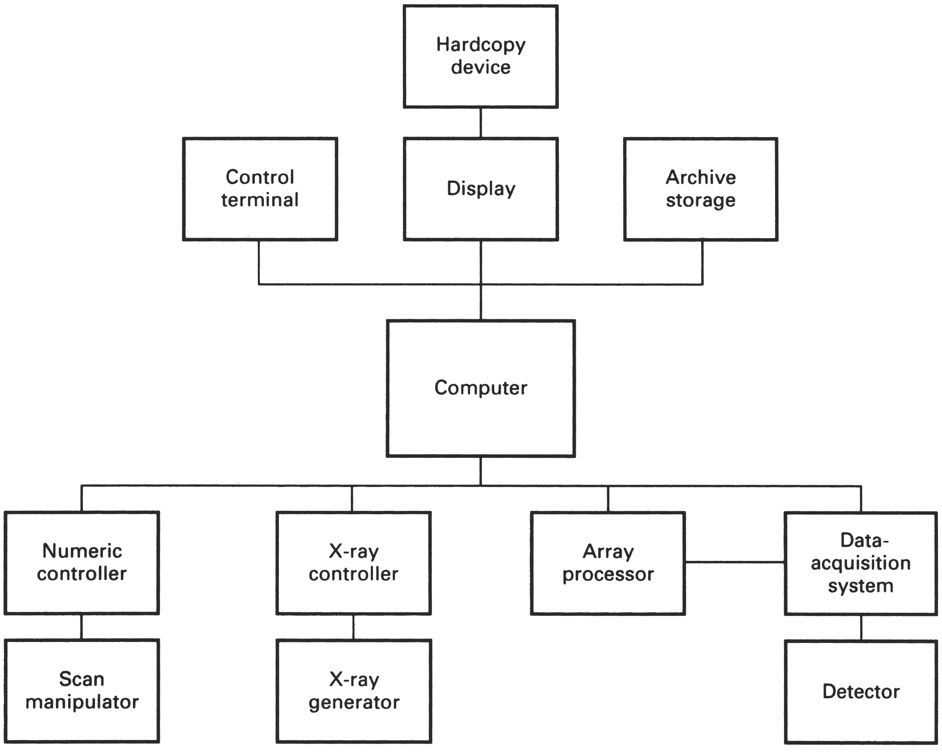


Fig. 15 Functional block diagram of a typical computed tomography system

Fig. 16 Automated industrial computed tomography system for the production inspection of small components. Parts-loading conveyor and cabinetized x-ray system are included in this setup.

- A data-acquisition system for converting the measured signal into a digital number and transmitting the data to the computer system
- A computer with appropriate software for controlling the data acquisition and reconstructing the projection from the measured data
- A display system for displaying the cross-sectional image

In addition to these individual parts of a CT system, the overall capabilities of the total system are also important. The key capabilities of a CT system are:

- The ability to handle the range of components to be inspected
- The throughput or rate at which the components can be tested

- The ability to provide sufficient image quality for the specified inspection task by considering the selectable operational parameters of CT systems that affect image quality

Computed Tomography Scanning Geometries

The CT scanning geometry is the approach used to acquire the necessary transmission data. In general, many closely spaced transmission measurements from a number of angles are needed. Four types of CT scanning geometries are shown in Fig. 17. Much of the historical progression of the data-acquisition techniques has been driven by the need for improvements in data-acquisition speed for medical imaging. In medical CT systems, the radiation source and detector are moved, not the patient. Industrial CT systems, however, often manipulate the component; this can simplify the mechanical mechanism and help maintain precise source-detector alignment and positioning. In either case, the relative positions of the object to the measured ray paths are equivalent. Some of the nomenclature derived from medical CT does not readily accommodate some of the manipulator configurations that are practical in industrial imaging.

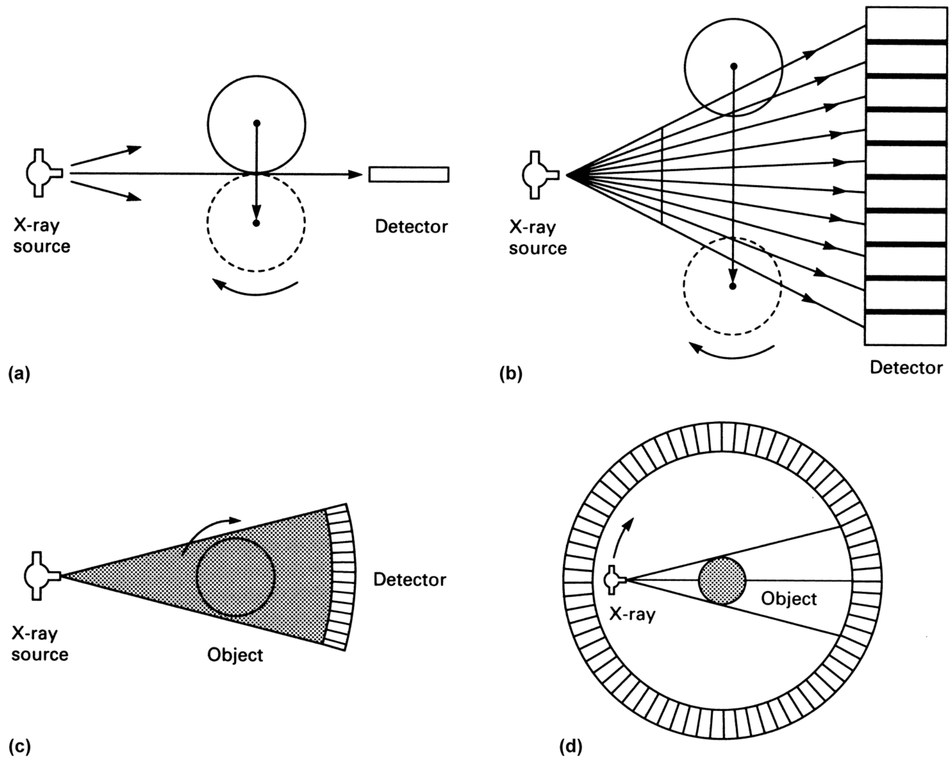


Fig. 17 Basic computed tomography scanning geometries. (a) Single-detector translate-rotate, first-generation system. (b) Multidetector translate-rotate, second-generation system. (c) Rotate-only (rotate-rotate), third-generation system. (d) Stationary-detector rotate-only, fourth-generation system. In medical systems, the source and detector are manipulated instead of the object.

Single-Detector Translate-Rotate Systems. The first commercial medical CT scanner, developed by EMI, Ltd., uses a single detector to measure all of the data for a cross section. The x-ray source and detector are mounted on parallel tracks on a rotating gantry (Fig. 17a). The source and detector linearly traverse past the specimen and make a series of x-ray transmission measurements (240 measurements for a 160 × 160 image array). These measurements correspond to the transmitted intensity through the object along a series of parallel rays. The source-detector mechanics are rotated by 1°, and another linear traverse is made. This provides another set of parallel rays, but at a different angle through the object. This process is repeated until data are obtained over a full 180° rotation of the source-detector system.

The original EMI scanner uses two detectors to collect data for two adjacent slices simultaneously; it is relatively slow, with nearly a 5 min scan time to produce a low-resolution image. Despite its limitations, this system was a significant breakthrough for diagnostic medicine.

Single-detector translate-rotate CT systems are sometimes referred to as first-generation systems. The use of the generation nomenclature was originated by medical manufacturers to emphasize the newness of their designs and is sometimes used as a matter of convenience to describe the operation of a system. Current commercial systems do not use the single-detector approach because of its limited throughput. The simplicity of this approach, however, makes it suitable for applications in basic research.

Multidetector Translate-Rotate Systems. To improve the data-acquisition speed, multiple detectors can be used to make a number of simultaneous transmission measurements. The second-generation or multidetector translate-rotate systems use a series of coarsely spaced detectors to acquire x-ray transmission profiles from a number of angles simultaneously (Fig. 17b). The data measurements are still acquired during the translation motion, but the system makes a much larger rotational increment. The distance translated must be somewhat longer than that for a single-detector system in order to have all source-detector rays pass over the entire object width, but fewer translations are needed to collect a full set of data. The mechanical system of a second-generation CT scanning geometry for industrial applications may range from a design for small components (Fig. 18) to a design for large castings (Fig. 19).

Rotate-Only Systems. Further improvement in data-acquisition speed can be achieved by using a broad fan beam of radiation spanning the entire width of the object, eliminating the translation motion entirely. The fast scanning speed of rotate-only systems is important in medical imaging to minimize patient motion during the scan and for high patient throughput. Nearly all current medical scanners are rotate-only systems, with some of these systems making more than 1 million transmission measurements for a complete scan in less than 2 s.

There are two basic configurations of rotate-only systems. Third-generation or rotate-rotate systems use many (sometimes more than 1000) closely spaced detector elements that are fixed relative to the x-ray beam (Fig. 17c). The source-detector combination may rotate together around the specimen, as in medical scanners (hence the term *rotate-rotate*). In industrial systems, the object can rotate to obtain data from all angles. The reconstruction process for these systems is slightly different than for the other configurations, because a transmission profile or view corresponds with a set of rays in the shape of a fan. The use of the term *rotate-only* in this article refers to third-generation systems.

Fourth-generation or stationary-detector rotate-only systems have a stationary ring of detectors encircling the specimen, with the x-ray source rotating around the specimen (Fig. 17d). The x-ray fan beam exposes only a portion of the detectors at any moment in time. The data are usually regrouped into fan beam sets, with the detector at the apex of the fan, or into an equivalent parallel ray set. This configuration is generally less flexible, cannot utilize the ability to manipulate the object, and is normally not found in systems designed for industrial use. Fourth-generation