XIM: X-RAY INSPECTION MODULE FOR AUTOMATIC HIGH SPEED INSPECTION OF

TURBINE BLADES AND AUTOMATED FLAW DETECTION AND CLASSIFICATION

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INTRODUCTION

     Under military manufacturing technology funding, a production proto-
type X-ray Inspection Module (XIM) has been established at General Elec-
tric Corporate Research and Development (GE-CRD) and delivered to Quality
Technology (QT), General Electric Aircraft Engine Business Group (GE-
AEBG). A company funded production unit has been built by GE-AEBG and
delivered to the GE-AEBG manufacturing facility in Madisonville, Kentucky
where it is in use in production. Computerized tomography (CT) and digi-
tal fluoroscopy (DF) images are produced with the system. The CT images
provide an image cross-section, and the DF images are much like chest
X-rays.The system was designed to automatically inspect and analyze flaws
present in turbine blades. It was applied to two flaw types; each type in
a different turbine blade. The image processing is performed on complex
gray scale images with varying background. The XIM system may be used
either automatically or in a manual mode with a trained operator to
interpret the images and make quality decisions.

     The XIM requirements were established to meet the needs of quality
inspection of small parts, like turbine blades, which are produced in
volume. The XIM scans a region 2.5 inches in diameter by 6 inches high.
Automatic part handling, highly parallel data collection, high speed
computation with array processors, and fast CT image reconstruction with
a modular image processor (MIP) have been essential to the realization of
these requirements. The reconstruction times for CT images are of such
duration, tens of seconds to minutes for a slice ten mils high, that in

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most instances it is desirable to scan a part for the presence of a flaw with a DF image. With a DF image, ambiguities can remain concerning the flaw, such as wall thickness, which can be resolved with a CT image. The CT capability provides a new dimension for factory X-ray inspection, the ability to image along the direction of the incident X-ray beam. The DF and CT capabilities are complementary. They are both useful independently, and are extremely powerful when used together.

An automated system is difficult to utilize in a factory setting unless a friendly interface is provided for factory use of the system. This need is met by directing the system with an inspection plan (computer software routines) in making the images, in analyzing them, and in forming a report of operator and/or automatic results. The inspection plan provides the same function as a parts program in NC machining: a flexible capability to image a particular turbine blade and establish the presence of a particular flaw.

SYSTEM DESCRIPTION

The system is comprised of hardware for manipulating parts, generating X-rays and detecting X-rays, hardware for information transmission and computation, software for controlling the XIM system and performing computations.

Parts are carried into the machine by a conveyor. An operator loads parts into universal grippers which are held to the conveyor by a platten. When the conveyor advances to deliver a gripper with part to the inspection location inside a lead shielded chamber, a numerically controlled manipulator removes the gripper and part from the conveyor, moves it in the appropriate path through the X-ray beam, and returns it to the conveyor. As the conveyor continues to advance and a part emerges from the chamber, panel lights inform the operator of the correct disposition of the part at the unload station.

For DF images the part is held at a constant angular position and moved vertically through the X-ray beam. For CT images the part is held in a constant vertical position and rotated through 360 degrees. Every sixtieth of a second the intensity of transmitted X-rays is collected from the elements of the xenon gas detector. Rapid data collection from high resolution detector elements is a major feature in the ability of the XIM to work with parts which are made in volume and which require high resolution inspection. The detector is connected by coaxial cables to a multichannel data acquisition system (DAS) which digitizes the signals.

The digitized signals from the DAS are transmitted to an array processor (APA), where they are normalized for changes in X-ray tube output and for channel gain and sensitivity variations, and where the logarithm of the data is taken. The output from APA is a DF image if the part has been scanned vertically. In the case of CT images, for which the part is rotated, the output of APA is a set of angular views which must be processed by convolution and back projection to obtain the CT image. Convolution is accomplished in a second array processor (APB) which passes data on to an image processor (MIP). There the back projection is performed. In this manner DF images and CT images are generated and transmitted to the VAX data disk. A CT image of a TF34 turbine blade is shown in Figure 1. The flaw visible in that image is the result of a cooling hole drilled from the trailing edge of the blade into an internal cavity and overdrilled into the far wall of the cavity.
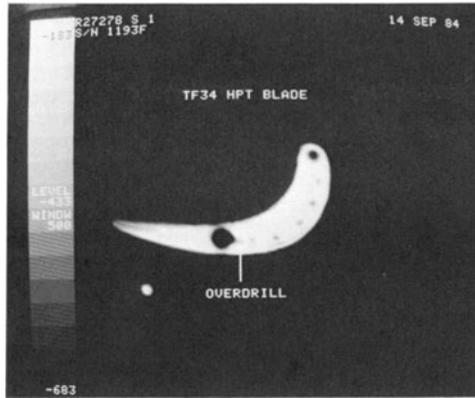
Fig. 1 CT image of a TF34 High Pressure Turbine Blade

The data acquisition operations which have just been described must be synchronized with part manipulation, activation of the X-ray tube, image processing, display of images, part loading, part unloading, input of operator decisions, and printed report generation. The software for the system consists of the programs which direct the real-time system and those which provide an environment for image processing and inspection plan generation. The real-time system is controlled by the executive software which starts tasks, monitors tasks, checks error conditions, initializes the system, and interfaces to the operator. There are three major subprograms which are spun off as independent processes under supervision of the executive. These are data acquisition, display on the Lexidata color graphics monitor, and automatic image processing. While data is being acquired for one blade, data acquired previously for another blade can be displayed to an operator for his decisions, and, at the same time, automatic image processing can be performed on the data acquired previously. Utilization is made of the overhead time in mechanically positioning parts, or in an operator making his decisions and entering them.

The form of the inspection plan is a major factor in friendly inter-face to XIM. The details of the scan and the image analysis are all sent to the XIM by the inspection plan. The executive software interprets the segments of the plan and sends information to the appropriate subpro-grams.

The manual image analysis portion of the inspection plan provides instructions to the display subprogram. It registers the image on the display and sets the gray scale or pseudo color scale. It can include image processing commands and cause the results of that processing to be displayed. While the display subprogram is invoked, the operator has the opportunity to enter his observations. This is done with a stylized code and a bar code reader for operator speed. The commands in this portion of the inspection plans are high level image processing commands. They invoke the same operations on image data as in an off-line image pro-cessing session.

The automatic image analysis portion of the inspection plan provides instructions to the automatic image processing subprogram. This subpro-gram carries out image analysis, evaluates criteria for the presence of a flaw and writes the results to a file. This file is used by the executive in conjunction with results from manual image analysis to print out reports and to light the disposition lights at the unload stations for the operator. The commands in this part of the inspection plan are high level Image processing commands.

Image processing in XIM encompasses the location of a region of an image where a specific flaw may reside, the automatic extraction of parameters from that region of interest, and the use of those parameters to decide automatically the presence or absence of a flaw. Processing is performed on the region of interest rather than on the entire image to reduce computation time. For clarity, the procedures used to do this will be described by means of a specific example, the meniscus geometry flaw in the TF34 high pressure stage 1 turbine blade. That blade is shown in Figure 2; the airfoil portion is about 1 1/8 inches long by 3/4 inch wide.

The blade is cast with a number of vertical interior cooling passages. One of these passages, the seventh from the leading edge, is about 0.06 inch in diameter and is closed off at the top by brazing in place a small plug. If the braze operation is successful, braze material flows

Fig. 2   TF34 Turbine Blade

to the bottom of the plug and forms a meniscus. If the meniscus is insufficiently complete, the part is rejected. These conditions are shown in Figure 3.
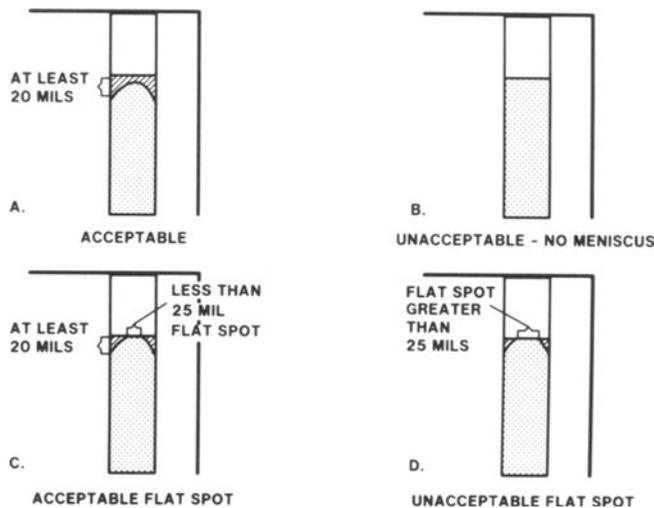

Figure 3. Meniscus Geometry TF34 Blade

The image processing algorithms must extract the shape of the cavity from the X-ray image. The region of interest in the image is shown in Figure 4 A. The image has been automatically registered by image processing to remove the 20 mil variations in mechanical positioning which can result from hand insertion of cast blades into any of the 25 grippers on the conveyor. The region of interest has been selected and displayed. Although the cavity and meniscus can be readily seen, there are two major image processing challenges: removal of the intensity variation in the background so that it will not affect thresholding, and location of the correct edge position which is blurred by the finite point spread function of the imaging system.
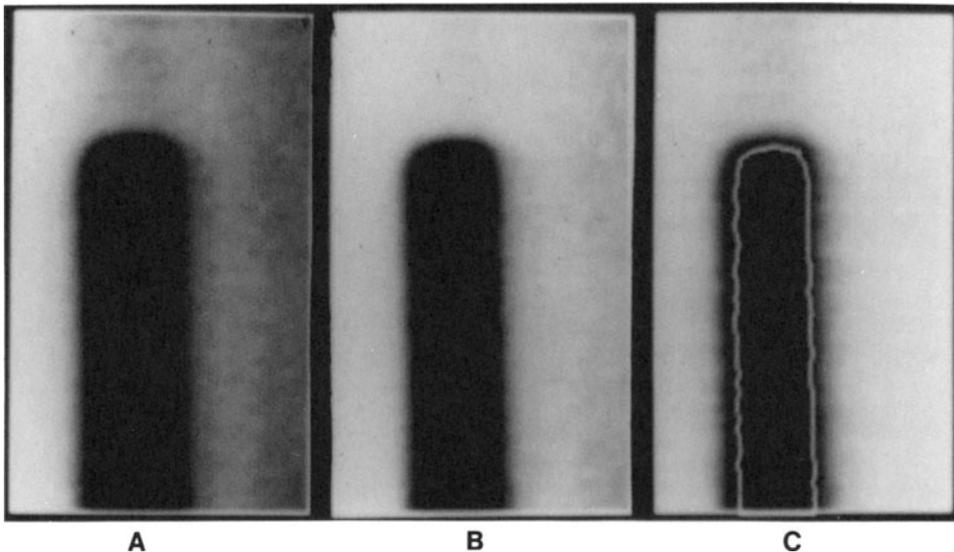

Figure 4   TF34 Meniscus Geometry Region of Interest

The DF image in Figure 4 is made of a blade in an intermediate stage of manufacture, before holes are machined into the trailing edge, and before a hole is drilled through the brazed plug. The presence of the plug, which has slightly different X-ray absorptivity than the blade material, is just detectable in the image above the meniscus.

The intensity variation in the background is greater horizontally than vertically because of airfoil thickness variation from leading to trailing edge. The horizontal trend is removed by comparing intensity for a row of data at the edges of the region of interest and making a linear correction. The data now has only a vertical trend which is removed by adjusting the row values so that the first column value is the same for

all rows. The region of interest, with background removed, is shown in Figure 4 B. The next step is to locate the top of the cavity by detecting the greatest transition in the vertical direction in the data. The position where the cavity just begins must be extracted, rather than some position in the transition region. When the top of the cavity has been found, the intensity value at this point is selected as a threshold value. Pixels with intensity values equal to or below the threshold value are assigned to the cavity and its boundary is defined. This boundary is shown in Figure 4 C where a bright display intensity has been assigned to all pixels on the boundary. Note that the boundary is slightly inside the edge which one might extract visually. This occurrs because of the finite point spread function of the system, and it is an example of the fundamental difference in what is measured automatically by the XIM and by an inspector. From the boundary parameters, obtained with image processing, the presence of a flaw can be ascertained.

The presence or absence of a flaw must be related to present industrial radiographic practice if it is to be transitioned into a manufacturing facility. A trained inspector examines a film image through a 10 times magnifier with a calibrated reticle. The inspector mentally estimates the presence or absence of a flat greater than 25 mils in extent. This observation can be performed within limits of about + - 5 mils. In contrast, the digital image processing information gives locations of the boundary at the top and at 10 mil intervals down the sides of the boundary. It has a repeatibility somewhat better than one pixel, but an absolute capability of about + - one pixel or 5 mils. Both the digital data and the inspector's reference results have finite variance, and the two measurements are of different quantities. Inspector measurements and XIM measurements were made on a population of blades and a linear regression analysis was performed on the two sets of results to establish an acceptance-rejection criterion. The estimator used from the image processing parameters was the ratio of the width of the cavity one row below the top to the average width of the cavity determined from the fourth, fifth, and sixth rows below the top. The use of a ratio makes the measurement insensitive to slight errors in calculation of system magnification, and it reduces the granularity of the estimator which occurs because the data is spatially sampled. The result of the regression is a linear equation which predicts the width of the flat in mils from the estimator value. This criterion was successfully applied to 68 blades run sequentially through the XIM at production rates with the image processing and classification operating in real-time.

XIM PERFORMANCE

The XIM performance was established by running automatically with automatic image processing using gauges and populations of turbine blades as samples. The meniscus geometry was detected in the TF34 blade and a second flaw type was detected in a F-404 blade. Goals of 90% probability of detection of flawed blades at 95% confidence were exceeded. Automatic detection of a 2-2T standard resolution test gauge one quarter inch thick was achieved repeatedly. The CT resolution standard was a hole ten mils diameter by ten mils long in a one quarter inch diameter superalloy rod. It was repeatedly detected with the XIM using automatic image processing. Cooling passage diameters were measured automatically using automatic interpretation of image intensity data to plus or minus five mils for holes about 10% of part thickness.

For all of the imaging, image processing, and image interpretation experiments conducted, the XIM throughput was limited by the data acquisition, rather than by image processing time. It should be emphasized that only one flaw condition was addressed at a given time, and, there-

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fore, the image processing time was minimal. As more flaws are added to a given inspection plan, the time limiting events may change.

CONCLUSIONS

The XIM provides new capability to make digital DF and CT images at a rate consistent with inspection of parts produced in volume. Automatic image processing and flaw identification have been demonstrated with good repeatibility and probability of detection. The system provides a friendly interface to the factory. As with NC machining, part programing is required for each new part and flaw encountered. The technology has been successfully transitioned into the factory because of several factors. Technically competent staff were applied in both GE-CRD and GE-AEBG. Two GE-AEBG employees worked at GE-CRD for several years and took their knowledge and experience to GE-AEBG. A functional, but slow system, was built at GE-CRD and used in GE-AEBG on factory hardware and problems during the three years before the completion of the XIM. A production XIM similar to the system being built at GE-CRD, was built at GE-AEBG, Evendale, and shipped to the GE-AEBG factory in Madisonville, Ky. prior to the completion of automatic image processing capability. It has been used in the factory in a manual mode awaiting completion of the image processing software. The transition of technology has been continuous during the project.

ACKNOWLEDGEMENT