INTRODUCTION

One of the most important characteristics of any imaging system is spatial resolution. This report describes a custom linear array Xenon ionization chamber detector developed by GE for sub-millimeter spatial resolution applications. The suitability of such a detector for high resolution digital imaging of turbine blades in both Digital Fluoroscopy and Computed Tomography modes is demonstrated.

In X-ray systems, spatial resolution is determined primarily by the effective source aperture, the effective detector aperture, and the imaging geometry. This report describes the measured spatial resolution characteristics of a digital X-ray Inspection Module (XIM) developed for airfoil inspection by General Electric under Air Force Contract F33615-80-C-5106. The XIM is one of a series of nondestructive inspection devices developed under the Integrated Blade Inspection System (IBIS) Program. A more general description of the IBIS XIM is given in [1].

Blades are a critical component of aircraft gas turbines. These parts undergo high temperature thermal cycling and very high stress. In order to meet these requirements, modern superalloy materials are widely used. As a result, critical flaw sizes are quite small. The major goal of the XIM system is to find flaws in turbine blades as small as 0.010 in linear dimension and assess their impact on blade performance. This report describes the spatial resolution characteristics of the XIM system.

SYSTEM HARDWARE CONFIGURATION

The XIM system is designed to inspect turbine blades with approximately 0.010" resolution. These blades fit into a part envelope 3 inches in diameter and 12 inches high. In order to achieve reasonable inspection rates, it is very desirable for both the X-ray beam and the detector to span the 3 inch part diameter. Therefore, a fan beam inspection configuration with a linear array detector is required. With this configuration, a DF image data set can be generated by scanning the part vertically past the linear array detector, and a CT image data set can be generated by rotating the part at the appropriate height for the CT slice. The data acquisition configuration for these two imaging modes is depicted...
in Figure 1. In the XIM, the data is handled in pipeline fashion, and the completed image is available essentially as soon as the data acquisition is complete.

![Fig. 1. DF and CT Data Acquisition](image)

Fig. 1. DF and CT Data Acquisition

The X-ray source in this system is a Phillips industrial X-ray tube which operates from 230 kilovolts peak (KVP) to 420 KVP. This range of energies is required to provide adequate penetration of several inches of nickel based superalloy. The absorptivity contrast at these energies is still quite sufficient to provide high quality images of small flaws. The fan angle of the tube is approximately 30 degrees. Since spatial resolution is a key concern, the tube is typically operated in small focal spot mode (1.5 mm spot size). Large focal spot mode (4.5 mm) is also available, and comparisons of results in the two modes are described in the Results Section.

The detector is essentially the key element in the system, since it provides the required spatial resolution. In order to provide 0.010" resolution, the sampling theorem [2] requires that individual detector elements must be spaced on 0.005" centers. To cover the 3" diameter of the inspection field of view, at least 600 detector elements must be provided. This number of elements implies a system of substantial complexity, both in the detector itself, and in the associated data acquisition elements.

In addition to providing a large number of closely spaced individual elements, the detector must have high quantum efficiency for effective imaging, and the reliability of the detector must be good for use in the factory. In order to meet these requirements simultaneously, a Xenon ionization chamber linear array X-ray detector was developed by General Electric for use in the XIM system. This report summarizes some of the key characteristics of that detector which affect spatial resolution.

The requirement for a 600 channel linear detector array in a 3 inch space led to the choice of a Printed Circuit Board (PCB) implementation of a multi-element Xenon ionization chamber. In order to achieve the required
spacing with sufficient accuracy, advanced photolithography techniques are required. This technology was developed at General Electric Corporate Research and Development early in the program on a prototype 64 element detector, [3]. The 600 element XIM detector was developed next. The detector board forms one plate of a parallel plate capacitor which resides in a pressure vessel. A high voltage plate is attached above the detector plate, and high pressure Xenon gas is the ionization medium. The finger spacing is uniform over the region contained in the pressure vessel, then it fans out to the connectors on the edges of the board.

A second major factor driving the use of PCB technology is the requirement of bringing 600 leads out of the Xenon pressure vessel. With the PCB, this can be achieved by simply passing the circuit card through the rear pressure vessel flange and making cable connections to flat ribbon cable. This is a major simplification over alternate connector techniques. A photograph of the 600 element XIM detector board mounted in the pressure vessel is shown in Figure 2.

In order to achieve comparable resolution in the vertical direction for DF imaging, a resolution of 10 mils with data taken in 5 mil steps is again required. The spatial resolution is achieved by collimation. Two tungsten blocks thick enough to attenuate the incident beam by a factor of 1000 are spaced 10 mils apart in front of the ionization chamber detector. This aperture defines the slice thickness in CT imaging.

The length of the detector elements in the X-ray beam direction and the X-ray absorption properties of the Xenon dielectric [4] determine the quantum efficiency of the detector. The effective energy of an X-ray tube operated at 420 KVP is approximately 250 keV. The quantum efficiency of the XIM detector at this energy is about 70%. In order to achieve this efficiency, a Xenon pressure of 75 atmospheres is required.

The imaging requirements leading to the detailed detector specification have been discussed. Spatial resolution is the major constraint driving the design. The detector is a 600 element linear array ionization chamber, implemented in PCB technology. The individual elements are spaced on approximately 5 mils centers. Horizontal resolution is on the order of 10 mils for a Xenon pressure of 75 atmospheres. Tungsten collimators limit the vertical slice height to 10 mils, and data is taken in 5 mil steps. The measured spatial resolution of this detector is the major topic of this report.

SPATIAL RESOLUTION CONSIDERATIONS

The spatial resolution of an X-ray inspection system is determined primarily by the focal spot size of the X-ray source, the detector element width, and the position of the part relative to the source and the detector. Suppose SS is the width of the focal spot, DIA is the width of the target, D1 is the distance from the focal spot to the target, and D2 is the distance from the target to the detector. The width of the penumbra (region where any part of the beam is blocked by the target) at the detector plane is given by

\[ X_2 = SS \times \left( D_2/D_1 \right) + (1 + D_2/D_1) \times DIA. \]

This expression consists of two terms, one due to the focal spot size SS and one due to the width of the target DIA. For a point target (DIA = 0), the projected size of the focal spot at the detection plane is simply SS*(D2/D1), which is otherwise known as the unsharpness of the image due to focal spot size [5]. For a point source (SS=0), the shadow of the target on
the detector plane is \((1 + D2/D1) \times DIA\), which is a magnified image of the
target with magnification \(M = (1 + D2/D1)\).

The system magnification (i.e., the distance ratio \(D2/D1\)) and the
detector element width are determined by the required system resolution.
This is done by specifying the target size which must be resolved, \(DRES\). In
the XIM system, \(DRES\) is chosen to be 10 mils. (The focal spot size is
determined once the X-ray source is specified. At this point, we know \(SS\)
and specify \(DIA = DRES = 10\) mils in Equation 1.) For an optimum system, the
focal spot size at the detection plane is set equal to the shadow of the
target at the detector plane.

\[(1 + \frac{D2}{D1}) \times DRES = (\frac{D2}{D1}) \times SS\]  

(2)

The result is given by

\[\frac{D2}{D1} = \frac{DRES}{(SS - DRES)}; \quad M = \frac{SS}{(SS - DRES)}.\]  

(3)

If the focal spot size is smaller than the target width, \((D2/D1) \times SS\) is
always smaller than \((1 + D2/D1) \times DIA\) and the system designer has one additional
parameter at his disposal to aid in system optimization.

The detector element spacing is determined by the required spatial
resolution and the sampling theorem [2], which requires two detector
measurements in each resolution cell. Since the spatial resolution is
specified at the part, the system magnification must be taken into account
as well in specifying detector element width. The result is

\[\text{ELEMENT SPACING} = \frac{(M \times DRES)}{2}.\]  

(4)

The vertical resolution and the CT slice thickness are determined by the
collimator height. The normal choice is

\[\text{COLLIMATOR HEIGHT} = M \times DRES.\]  

(5)

The measured magnification in the XIM system is 1.15.

The horizontal system resolution is affected by factors besides system
geometry. The primary factor involved in the XIM system is the interaction
of incident X-rays with the Xenon detection medium. As incident X-rays
ionize the Xenon molecules, both secondary electrons and secondary X-rays
are created. These secondaries travel away from the primary detection site
before they interact with the Xenon again, and the distance they travel
affects the spatial resolution. This distance is determined primarily by
the energy of the incident X-rays and the density of the Xenon gas. In
short, the detection process is not a strictly localized process, and
spreading is therefore introduced into the width of the system resolution
function. If the distance the secondaries travel is greater than the
detector element spacing, crosstalk between elements will be observed. The
spatial resolution of the detection process is described in more detail in
[6].

Resolution of an optical system is defined [7] as the minimum
separation of two adjacent points that is detectable by the system.
Resolution of photographic emulsion is expressed as the number of line pairs
per millimeter that can be distinguished. Since the XIM system is
essentially a filmless X-ray imaging system, the spatial resolution should
also be characterized by the number of line pairs per millimeter that can be
distinguished. Spatial resolution is, therefore, characterized by
measurement of the Modulation Transfer Function (MTF). The MTF for \(x\) LP/mm
is defined by
MTF(x) = (AL(x) - AP(x))/(AL(0) - AP(0)) \hspace{1cm} (6)

where AL(x) is the average signal amplitude through the lead lines of a standard resolution gauge at spatial frequency x, and AP(x) is the equivalent quantity for plastic lines. The denominator normalizes the results to the dc value, so the MTF ranges in amplitude from 0 to 1.

Spatial resolution as defined above clearly requires the ability to separately identify adjacent objects in the image. In certain imaging applications, detection of an object of a certain size is sufficient, and resolution of two closely spaced objects is not required. THE ABILITY TO DETECT AN OBJECT OF A CERTAIN SIZE IS A SUBSTANTIALLY EASIER TASK THAN ACHIEVING RESOLUTION OF COMPARABLE SIZE. As shown below, with the XIM system it is possible to detect objects of 1 or 2 mil diameter, even though the measured spatial resolution is between 10 and 14 mils. Therefore, it is critically important, when comparing imaging systems, to make the comparison based on the same criterion.

EXPERIMENTAL RESULTS

The measured spatial resolution characteristics of the XIM system are presented in this section. Under typical conditions, the X-ray tube was operated with a peak voltage of 320 kilovolts, and the focal spot size was 1.5 mm (60 mils). The magnification was 1.15. The voltage on the Xenon detector was 1000 V, and the Xenon pressure was around 1050 psig. Both horizontal and vertical spatial resolution were measured as a function of various parameter values around these nominal settings. If a specific parameter is not mentioned in the description below, it can be assumed that its value is the default mentioned in this paragraph.

The horizontal resolution characteristics are presented first. Figure 3 shows the measured horizontal MTF for the default values specified in the previous paragraph. (Slightly better resolution may be achieved for other parameter values). The graph shows a MTF of 5.4% at 2.8 LP/mm. At 2.9 LP/mm, the data no longer resolves 5 plastic lines and 4 lead lines. Therefore, the horizontal resolution of the detector is quoted at 2.8 LP/mm. At this spacing, each structure in the gauge (lead or plastic line) has a width of 0.179 mm = 7 mils. However, in order to resolve (differentiate between) two structures of this width, they must be separated by 14 mils. Hence the resolution is 14 mils.

Horizontal resolution is determined both by spreading of secondary radiation and by the interelement spacing. Tam's model of secondary spreading \[6\] predicts a Full Width at Half Maximum of 6 mils for the spreading of secondaries in Xenon gas at a density of 1 gm/cm\(^2\) for a typical 320 KVP tube spectrum. In conjunction with a finger width of 5.8 mils and a projected focal spot size (Eq. 1) of 9.1 mils, this implies a horizontal resolution of 10.2 mils. Uncertainties in the shape and size of the focal spot and the spreading of the secondary radiation probably account for the discrepancy with measured results. In any case, it is clear from this measurement that for the X-ray energies and Xenon pressures involved, closer spacing of the individual detector elements would not be fruitful.

The measured horizontal resolution function using the large spot of the X-ray tube is shown in Figure 4. Here, the MTF is 7.8% for a line spacing of 1.3 LP/mm. The difference compared to Figure 3 is strictly due to the much larger size of the focal spot in this measurement (4.5 mm instead of 1.5 mm). The result is generally consistent with the standard model of system resolution width \[5\] in which the total resolution width is given by the square root of the sums of the squares of the X-ray source width and the detector element width (including secondary radiation effects).
The measured vertical resolution MTF is shown in Figure 5. Here, 4.0 LP/mm data is resolved with an MTF of 10.2%. Each structure has a width of 0.125 mm = 4.9 mils, and the quoted resolution is 9.8 mils. The vertical resolution in the system is essentially determined by the collimator opening. If a better resolution in this direction were required, it could be achieved by narrowing the jaws of the collimator. However, the resulting reduction in X-ray flux would reduce the available signal to noise ratio.

The measured vertical resolution function using the large spot of the X-ray tube is shown in Figure 6. The MTF is 9.3% for a line spacing of 3.7 LP/mm. Even though the focal spot size is 4.5 mm, the measured resolution is only slightly different from the case of a 1.5 mm focal spot size. The 10 mil tungsten vertical collimator limits the effective spot size dramatically, and prevents any significant degradation in resolution.
This result is, of course, significantly different than the horizontal resolution case, where no collimator is available to reduce the effective spot size.

The effect of Xenon pressure on system performance is important and somewhat surprising. Detector signal amplitude as a function of Xenon pressure is shown in Figure 7 for 2 individual elements of the 600 element XIM detector. These channels are representative of detector performance in general. Signal amplitude in the 2 elements varies slightly, but the shape of the curve is the same in the two cases. Signal amplitude has a broad maximum around 800 psig, and drops rather quickly above 950 psig. Nonetheless, system resolution continues to improve at least up to 1000 psig, as shown in Figure 8. Improvement in spatial resolution with pressure is expected since the density of the Xenon is increasing rapidly with
pressure in the 600 to 1000 psig range, and the range of secondary radiation in the ionization chamber decreases with increasing density. The observed signal amplitude behavior is more difficult to explain, however, it is consistent with increased ion recombination rates and lower ion mobilities at higher gas densities. A more detailed explanation requires further investigation.

Fig. 7. Detector Signal vs. Xenon Pressure

Fig. 8. System Resolution vs. Xenon Pressure
The spatial resolution properties of the XIM system were described in the last few paragraphs. The system, however, is capable of detecting much smaller objects. This capability is presented in Figure 9, where a DF image of 3 tungsten wires encapsulated in glass is displayed. The two outer wires are 2 mils in diameter and the center wire is 1 mil in diameter. All three wires are clearly visible in the image, though the 1 mil wire is near the detectability threshold. These images demonstrate the necessity of properly specifying the characteristics of an imaging system in order to meet the necessary performance requirements without overspecifying and adding unnecessarily to the cost.

CONCLUSIONS

The XIM system was specifically designed for turbine blade imaging applications. Typical blades and both DF and DT images are shown in [1]. The XIM has been remarkably successful in meeting its blade inspection goals, and two systems are now installed and operating in GE aircraft engine manufacturing plants. The spatial resolution is clearly satisfactory for this challenging application, and the custom GE Xenon ionization chamber detector is a key element in the success.

ACKNOWLEDGEMENTS

The author would like to acknowledge the contribution of N.R. Whetten to the development of the first experimental printed circuit board Xenon detector. D.S. Steele carried the development through the pre-prototype and prototype stages, and is now responsible for the detector effort at GE Aircraft Engine Business Group in Evendale, Ohio. C.R. Trzaskos was responsible for detector fabrication.
REFERENCES


DISCUSSION

From the Floor: Maybe I misunderstood, but did you say that in the image, you wanted to make the contribution of the source and the magnified image of the target the same? Is there some reason for that?

Mr. Eberhard: Yes. The best way to look at that is to assume you have two objects separated by a gap of width equal to the system resolution, DRES. You then choose the distances D1 and D2 such that the penumbras of the two objects just touch at the detection plane. This is the limiting case in which you can resolve the two objects. It also corresponds to the situation where the contribution of the source and the magnified image of the target are the same.

Mr. John Goss: In the CT scans I've seen, the cracks in the material are basically a gray smear across the image. If I take a photograph of the crack and I take a look at the CT scan I have to do a lot of inference to try to figure out where the crack really was.

Mr. Eberhard: The detectability depends on a lot of factors. The major point is that you can typically detect things in a system before you can resolve them. For objects smaller than the size of the system resolution function, the CT image of the object is typically larger than the object itself, so determination of size and position are difficult. Also, if two small cracks were present in the image, you can detect the presence of the cracks before you can resolve the presence of two separate objects.

Mr. Goss: Well, if the two cracks were parallel and, say, 28 mils apart, could I distinguish between the two?
Mr. Eberhard: In this system, if they are 28 mils apart and you have sufficient contrast to see the cracks, you should be able to tell that there are two of them.

From the Floor: Were you seeing cracks with CT or with Digital Fluoroscopy?

Mr. Eberhard: The resolution measurements presented here were taken in Digital Fluoroscopy mode. We have certainly seen small flaws in CT as well, but we have not yet attempted to make quantitative measurements.

Mr. Oliver: Jeff, there is the experience with the CT gauge. We made a gauge with a very small hole in the middle of it. This was done by taking a rod, cutting it in half, grinding it flat, putting a tiny hole in it, and then gluing it back together under pressure so that the interface was no more than several 10,000ths of an inch thick. All we could see was the interface. The CT method can be very sensitive to cracks. But it hasn't been qualified.

From the Floor: What is the resolution you can get if you improve your system by using a microfocus X-ray source?

Mr. Eberhard: In the current geometry, the problem is still that you have finite detector aperture effects and you still have the spreading of the secondary radiation in the detector. Therefore, as the spot size decreases, these detector effects will quickly become the key contributor to the width of the system resolution function, and I wouldn't expect a substantial improvement from using a microfocus source.

On the other hand, if you switch to a high geometric magnification geometry, or you collimate the detector instead of using an array, you should be able to do much better.

Mr. Oliver: Last question.

From the Floor: We have seen delaminations in some composite structures down around 5 mils with conventional CT systems.