Development of Automated NDT Systems

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Abstract

This paper describes:

1. A software package to generate radiographic techniques. It also can convert all grey levels on any radiograph to enable any specimen thickness and defect through thickness to be measured.
2. An automated digital real time radiographic system to x-ray the whole wing of an aircraft.
3. An automated ultrasonic system to detect cracks around all the rivets of an aircraft wing.

1. A software package to generate radiographic techniques

The software relies on a mathematical model for a radiographic exposure chart (E.g. Fig. 1). One kV line on an exposure chart, which represents the relationship between exposure and material thickness can be represented by the equation:

\[ E = A \cdot 10^{B \cdot V \cdot T} \quad (1) \]

Where \( E \) = Exposure (mA x exposure time)
\( V \) = kV
\( T \) = Specimen Thickness
A and B are Constants

The software requests the coordinates of two points on this kV line (ie two sets of E and T values). It is then able to calculate the values of the A and B constants for this kv line. Different kV lines will have different A and B values. The software then requests the coordinates of two points from each of at least five other kV lines and calculates the respective A and B values. A and B vary with kV and equations which represent this variation quine closely are:

\[ A = F \cdot V^G \quad (2) \]
\[ B = H \cdot V^J \quad (3) \]

where F, G, H and J are constants.

The software then uses least-squares routines to automatically calculate the F,G,H and J values.
Films can also be modelled by requesting 6 coordinates from a film curve which is represented by:

\[ E = K \cdot D^M \]  

Where: 
- E = Exposure
- D = Density
- K and M are constants which again are calculated by the least squares technique.

To calculate a technique for a specimen the software uses the following equations:

\[ E = A \cdot 10^{(B \cdot V \cdot T \cdot \text{MATERIAL})/2} \cdot (\text{DENREQ}/2)^M \cdot (\text{FF}/\text{FFX}) \cdot (\text{FFD}/\text{ECFFD}) \]  

\[ E_T = mA \cdot \text{TIME} \]

Where: 
- E = Exposure to be calculated
- MATERIAL = Material equivalent factor when the material to be radiographed is
different to that used in the exposure chart

\[
\begin{align*}
\text{DENREQ} &= \text{Density required for the radiograph} \\
\text{FF} &= \text{Film factor of the film to be used in the technique} \\
\text{FFX} &= \text{Film factor used in the exposure chart} \\
\text{FFD} &= \text{Film to focus distance to be used in the technique} \\
\text{EXFFD} &= \text{Film to focus distance to be used in the exposure chart} \\
\text{E}_T &= \text{Technique exposure} \\
\text{mA} &= \text{mA required for technique} \\
\text{TIME} &= \text{Exposure time required for the technique}
\end{align*}
\]

After all the relevant data for the technique is entered into the software, Eq. 5 is “looped” by increasing “V” gradually from 1 until \( E = E_T \). Hence the software is calculating the final required kV. A typical technique is shown in Fig. 2.

Another option allows the input of a particular kV value and the density of the film produced is given at this kV value. This allows curves of the type shown in Fig. 3 to be generated. This chart was produced by the software by keeping the kV calculated constant and varying the thickness to calculate the density at this thickness. The other kV curves were produced by calculating a technique with a different kV for the specimen thickness and then the extrapolated kV calculated as required. This chart is valuable because it shows the film density which would be produced on a radiograph with a particular kV and hence all the radiographic density values on a film in any technique could be converted into specimen through thickness. The value of this is that:

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**Fig. 2** A radiographic technique generated by the software
1. All the density values on a film could be predicted in the thicknesses of the specimen are known.
2. The measurement of specimen thicknesses and the through thickness dimension of defects from density measurements on a radiograph is possible.
3. The contrasts and film latitudes produced by various kV’s can be predicted and hence an appropriate kV could be selected which produces the required contrast.

Fig. 3 A software generated plot of density versus thickness at different kV values

Fig. 5 shows the prediction of density variation across a weld in Fig. 4 or the measurement of thickness from the density variation across the weld. Similarly Fig. 6 shows the prediction of density variation across a defect in Fig. 4 or the measurement of the defect through thickness from the density variation across the defect.

Fig. 4 Weld radiographs
2 Robot Guided X-Ray System for Aircraft Wing Inspection

A robot guided digital X-ray imaging system as shown in Fig. 7 was developed for automatic aircraft wing inspection. The manipulator system automatically moves the x-ray tube and the digital sensor along the wing of the aircraft. Digital radiographs are taken as the system moves...
and the whole wing area can be built up gradually (See the green boxes at the right hand side of Fig. 7). A focus of attention is to inspect the fasteners along the wing spars.

Fig. 7 Robot guided scanning manipulator over aircraft wing

Digital radiographs of wing

Fig. 8 shows an aircraft wing spar radiograph. In this radiograph, line (fatigue) cracks created on specimens are taken along with the wing spar image. The cracks were first produced by a fatigue process on a thin aluminium plate, about 2mm thick. These plates were then placed on top of the wing to simulate cracks inside the wing spar. The cracks are circled in yellow. There are numerous fastener holes in each radiograph, and these areas are high risk regions for fatigue cracks.
4. **Automated ultrasonic and eddy current inspection system**

Fig. 9 shows the automated ultrasonic inspection of an aircraft wing.

**Fig. 9 Automated ultrasonic inspection of aircraft wing**
To inspect the cracks around a fastener hole of the wing, an angled shear-wave is produced using an appropriately orientated transmit/receive immersion compression wave probe (see Fig.10). The ultrasonic beam material surface entry point is positioned at an offset distance from the centre of the fastener hole. The probe system is rotated around the hole to detect cracks that may occur anywhere around the circumference (see Fig. 10(d)). The sound wave penetrates the material tangential to the circumference of the hole. The position of the beam entry point from the fastener hole varies with the thickness of the wing skin as well as the size of the fastener hole.

For a through-hole, as shown in (a) and (b), the cracks are likely to occur at the top and bottom surface of the wing skin. To detect cracks at these locations, an ultrasonic beam with a refracted angle of 45° is required. For a countersunk hole, cracks can occur at the bottom skin surface, as in the case of the through-hole, and also at the neck area of the countersunk hole as shown in (c). Therefore an ultrasonic beam with a refracted angle of 70° is required for the countersunk hole.

Fig.10. Possible crack patterns around fastener holes
Automating the ultrasonic inspection process therefore requires the system to be capable of deploying both the $45^\circ$ and $70^\circ$ refracted angle systems at different positions around the fasteners. In addition, as the angle of incidence of the ultrasonic wave is important for reliable detection of cracks, the system must be able to position the sensors normal to the wing surface while it is rotated around the fastener hole. Good ultrasonic coupling between the probe and the wing surface must also be maintained at all time. This can be monitored using the coupling monitoring probe shown in Fig. 10 (a) to (c) which monitors the reflected signal from the specimen surface. The automated system would also require a computer controlled ultrasonic instrument that can be programmed for gating and signal monitoring functions. As soon as coupling is lost the system should stop and only restart after good coupling is regained.

**Eddy Current Inspection**

The eddy current inspection technique which is part of the system also, uses a high frequency electromagnetic field as a probing medium to explore properties of material, and to detect surface as well as near surface internal defects. The electromagnetic field is generated by inductive coils fitted in the eddy current probe that is placed in close proximity to the surface of the material under test. The electromagnetic field would induce eddy current in the material and generates a secondary field opposing the primary field. The corresponding response generated by the eddy current, that is the strength of the secondary field, can be measured using a secondary coil embedded in the same probe. The response depends on the properties of the material under test. Defects in the material, such as cracks, can be easily detected using this method because a defect can cause huge changes in the eddy current and hence the magnetic field generated.

Eddy current probes are available in different sizes and shape, depending on the applications and the depth of penetration required. In the case of wing skin inspection, a small pencil probe is usually used. During inspection, a probe is placed near the edge of the fastener hole and rotated around the circumference to detect cracks near the top surface of the wing skin, as illustrated in Fig. 11. As the magnetic field generated by the eddy current probe usually does not provide deep penetration, this technique is usually employed for top surface inspection.

![Eddy Current Scan Path](image)

**Fig. 11 Eddy current scan path**

It is simpler to automate the eddy current inspection process than the ultrasonic technique, as there are no additional requirements of coupling between the probe and the surface under test. The automated system must be able to position the eddy current probe near the circumference of
the fastener holes and rotate about the centre of the fastener hole. Because the fasteners are ferromagnetic the radial distance of the eddy current probe from the fastener centre needs to be maintained to be fairly constant in order to reduce significant variations in signal response from the fasteners. However, because contact between the probe and the wing surface is required, some form of compliant device must be provided so that good contact is maintained while rotating around the fastener. As in the case of the ultrasonic inspection, a computer controlled eddy current inspection board is required so that test parameters as well as automatic analysis of eddy current responses can be monitored.

Conclusions

1. A software package to generate radiographic techniques has been described. The mathematical model is based on the exposure chart and film curve used for the technique. All radiographic densities on a film can be predicted if the specimen thicknesses are known. Alternatively all specimen thicknesses could be determined from the density measurements on the radiograph. Similarly defect densities are predictable if their through thickness values are known or alternatively defect through thickness values can be determined from their density measurements.

2. An automated radiographic system was described to inspect a whole aircraft wing for cracks inside the wing structure.

3. An automated ultrasonic and eddy system was described to inspect a whole lower aircraft wing skin for cracks.

References


