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on

Application of Non-Destructive Inspection Methods to Aircraft Structures

by

P. Gallinaro and R. B. Oliver

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

APPLICATION OF NON-DESTRUCTIVE INSPECTION METHODS TO AIRCRAFT STRUCTURES

by

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FOREWORD

The Structures and Materials Panel of the NATO Advisory Group for Aerospace Research and Development (AGARD) is composed of scientists, engineers and technical administrators from industry, government and universities throughout NATO, who are concerned with advancing the status of aerospace research and development and with developing technical means and data for optimizing the vehicles and equipment of interest to NATO. The Panel, therefore, provides a discussion forum, a mechanism for exchanging information, and a means for establishing and conducting cooperative studies and laboratory programs in selected technical areas.

Non-Destructive Inspection is an important and flexible tool in assuring safe and economical operation of modern aircraft – commercial or military. Precise knowledge of its methods and potentialities is necessary for all engineers engaged in aircraft maintenance, With the extensive application of fail-safe structures and of fracture mechanics methods for ensuring structural integrity, the designer must also understand the reliability and efficiency of the various Non-Destructive Inspection Methods.

Basically NDI offers various possibilities for measuring materials properties and defects in, or deviations of, the shape of structural elements (material flaws, surface roughness, cracks, corrosion, etc.). The main application for inspection of operational aircraft is location and measurement of cracks and corrosion defects.

Generally the available methods are satisfactory for most cases of metal structures, but there is a serious deficiency in NDI methods for production and acceptance of composite or welded primary aircraft structures.

The present publication contains two individual reports which cover survey trips made over the last four years in order to get a representative view of the NDI methods in use, their particular applications and related problems. 18 European and 1 American facilities were visited by the authors.

The Structures and Materials Panel expresses its appreciation to the authors for their significant contribution.

Theodor Gaymann
Chairman,
Working Group on Non-Destructive
Inspection Methods

AGARD Structures and Materials Panel.

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NON-DESTRUCTIVE INSPECTION OF STRUCTURES

P.Gallinaro

1. SUMMARY

This is a report to the Structure and Materials Panel of AGARD on a survey which was made in the NATO European countries during the months of May, June and July 1967 in connection with a project which includes further visits to organizations in U.S.A. and Canada.

The objective of the survey was: "To review the application of non-destructive methods of inspection of operational aircraft structures in the NATO countries in regard to equipment and techniques used, structural components examined and the reliability of results obtained".

Discussions have been held about some problems relevant to *in situ* inspection of bonded, welded, and riveted structures with particular reference to the use of X-rays, ultra-sound and eddy-currents. The time available for the discussions was too short, however, to allow a complete and detailed comparison of the experience gained and of the different opinions expressed.

Some documentation has been obtained from research laboratories, manufacturers, and airline operators, concerning the application of inspection procedures to structural joints and components of particular types.

The successful use of X-rays, ultra-sound and eddy-currents is increasingly being introduced in the field of aircraft maintenance, thanks to the cooperation between manufacturers and operators who, overcoming difficulties of accessibility, have often made it possible to perform quick and efficient *in situ* operations.

In ultrasonics, the efforts of researchers are aimed at developing techniques and equipment which allow the type and dimensions of the defects to be determined. Among the different achievements particular mention should be made of the use of more sensitive piezoelectric ceramic materials, focusing transducers and signal recorders, previously quantized (for example: using a Mufax Recorder manufactured by Muirhead & Co. Ltd.).

Adhesive bond testing problems are today under scientific investigation, particularly at Harwell AERA NDT Centre and by Fokker at Schiphol. A better understanding of the physical and mechanical characteristics of the bond is needed.

Several new experimental techniques are also under laboratory development with a view to possible applications in the field of material inspection (e.g. the revealing of the percentage of residual austenite) and for the detection of early fatigue cracks (using birefringent coating or by electron emission).

2. ACKNOWLEDGEMENT

The author is indebted to all the people visited; without their cooperation this survey would have been impossible. He particularly wishes to thank the managements of Breguet Aviation and Fokker for data concerning inspection of adhesive bonded structures, and AERE, AID, LABG laboratories for the documentation and information supplied on their research work.

3. CURRENT METHODS OF INSPECTION. GENERAL

In outlining the scope of the survey, the Panel's recommendations were as follows: "Through comparative assessment of the various applications:

(a) evaluate current practical experience in the field;

(b) isolate the best procedures;

(c) in general, stimulate research work aimed at improving accuracy of results, reliability of methods, development of new methods".

The inspection methods most used at present - in addition to the conventional optical, magnetic particle and penetrant detecting techniques - are based on electro-magnetic radiation (X and gamma radiography), elastic waves (ultrasonics) and eddy-currents.

As to equipment used for detection of surface defects (penetrant and magnetic particle methods) some minor innovations were found, namely:

ultraviolet ray lamps with sufficiently high brilliance to make the use of dark rooms unnecessary;

the use of dry magnetic powder held in suspension by compressed air: the inspection is performed more rapidly and hazards to health are minimized;

the use of steel blocks chrome plated on one surface and with Brinell impressions of different diameters on the opposite surface, for checking the overall performance of a fluorescent penetrant-materials system. The chromium plated block has a greater sensitivity than the previously used aluminium block (heated and quenched), which could be used three times.

Portable magnetic-particle and penetrant inspection units are usually employed in airline maintenance; the equipment can be moved to the aircraft and crack detection carried out without removal of the components.

It is in the fields of radiography, ultrasonics, and eddy-currents that most progress and development are now apparent. These methods are being used increasingly by airline operators for detecting *in situ*, quickly and reliably, cracks and corrosion in structures and components, particularly in those instances where a great deal of dismantling would be necessary to permit visual examination.

The operators generally follow the inspection procedures (or service bulletins) issued by the manufacturers, which contain all the details of the operation technique and give the specifications from which the operator can manufacture suitable standards.

X-rays, at first used for inspection of production castings and welded structures, have been used for fifteen years in airline maintenance for detecting fatigue cracks in thin sheet structures (e.g. tail plane, aileron, fuselage, etc.) where the majority of the cracks are located in rib flanges in contact with the outer skin. Among the innumerable cases are the following: wing spar caps, fuel tank compartments, landing gear fittings, turbojet combustion chambers, engine support tubes (for corrosion on the inner surface) etc. In some instances, when high sensitivity is not required (e.g.: detection of minute metal particles trapped in the oil cooler after engine failure, inspection of steel wires imbedded in the tire beads, etc.), paper, instead of radiographic film, is used for economic reasons.

Difficulty in positioning and unfavorable geometry of the structure under test, often make it difficult to obtain high sensitivity (1%);

The applications of gamma radiography, which requires prolonged exposure times for *in situ* structural inspection, include the use of iridium 192, thulium 170 (e.g. light alloys with total thickness up to about 1 inch) and cobalt 60 (e.g. combustion chambers).

Ultrasonic method has been used successfully in the last few years also for *in situ* inspection of hard-to-reach components and structural areas (riveted, welded or bonded).

Among the practical applications are: high-strength light-alloy landing gear cylinders (also for corrosion fatigue damage on the inner surface), main landing gear bogie beams (very high strength steel), spar booms, elevator torque tubes, front threads of propeller cylinders, engine mounting brackets, track for passenger seats (while mounted in the aircraft) steering rack of nosewheel, lower skin under riveted lap: of fuselage, wing plank splice gap (for corrosion and cracks), bonded joints (lap and honeycomb panels). spot welding, etc.

In general, the pulse echo method with single or dual probes suitably set at an angle to generate transverse waves (shear waves) is used, but also longitudinal waves (compression waves) and surface waves (Rayleigh waves) are employed; the latter to detect very small sub-surface fatigue cracks in sophisticated components (bogie beams).

The essential requirement is a suitable calibration block and this is generally provided by using an identical part, with small holes and grooves simulating the flaws, as a reference specimen.

The resonance method is used for measuring wall thicknesses when only one surface is accessible; e.g., inspection of residual local thicknesses on a tube corroded on the inner surface. For the atomic industry a very sensitive ultrasonic micrometer has been developed which is capable of measuring the local wall thickness of fuel element sheathing on an area of 1 mm^2. It is known that a wall-thickness variation can constitute a dimensional flaw in this application.

A commercial precision ultrasonic pulse-echo instrument is available which provides an extremely high inspection speed and is capable of resolving individual cycles of ultrasonic pulse*.

With *eddy-current* techniques wall thickness measurements are also possible, but the main use of this method is in aircraft inspection *in situ* for detecting and measuring fatigue cracking in holes (e.g. bolt and fastener holes, spark-plug bosses of engine cylinders, etc.) or on radius surfaces of components (e.g. wheels, compressor blades, shafts, etc.). The test coils used are of the probe type and are placed directly on and perpendicularly to the surface under test†; they offer the advantage of high resolution. Probe type coils are used also for measuring thickness of conductive and non-conductive coatings** (provided the conductivities of the coating and basis metal are sufficiently different) and for inspecting fire or heat damaged light alloy structures††. (There is a direct relationship between conductivity and heat treatment condition).

Eddy currents for *in situ* use in aircraft maintenance are increasingly used whenever accessibility is possible. The time to make an inspection can be vey short, e.g. by using special devices the 29 compressor "0" stage rotor blades of a turbojet engine can be inspected on the leading edge, centre section and trailing edge in 7 minutes.

When more than one area on a specific component must be inspected multi-probe devices which are suited to the geometry of the component to be inspected are used. These are provided with monitors (light or sound signal), the indications of which are affected only by cracks.

4. INSPECTION OF ADHESIVE BONDED STRUCTURES

4.1 General

Due to the widespread use of adhesive bonding in the aeronautical, space, and atomic industries - all of which have different inspection requirements - the literature and know-how now available in this field are considerable.

In modern aircraft structures adhesive bonded stringers, doubler and honeycomb sandwiches can be found. Bonding is also widely used for helicopter rotor blades.

In production, quality control methods are the following: in practice, ultrasonic techniques, even with their limits possibly integrated by radiographic controls (in the case of honeycomb panels), are generally adopted:

(a) ultrasonic resonance test;

(b) ultrasonic impulse-echo method;

(c) acoustic methods;

(d) depression cup method;

(e) radiographic inspection (only for honeycomb);

(f) thermal methods;

(g) temperature-sensitive coatings.

4.2 Ultrasonic Resonance Test

For all instruments of this type, a piezo-electric crystal is excited and the changes of frequency and/or amplitude, associated with mechanical resonance, as affected by discontinuities, homogeneity defects and adhesive thickness variations, are displayed on an oscilloscope or read on a microammeter. Variations in these two parameters are used as a comparative measure of bond "quality".

* Microradar Unit, Réalisations Ultrasoniques, Meaux (France).

† Defectometer Type 2154. Institut Dr. Foerster, Reutlingen,(Germany).
E.C. Test Equipment Type 600 and 700, C.N.S. Instuments Ltd., London (United Kingdom).

** Dermitron. Unit Process Assemblies Inc., Woodside, N.Y. (USA).

†† Magnatest FM-120. Magnaflux Corporation, Chicargo, Ill. (USA).

The following three devices are being used, but in Europe the author saw only the first being used. A Training Manual and an Operation Manual are available for this instrument.

– Fokker Bond Tester, manufactured by Fokker Aircraft;

– Coinda-Scope, manufactured by Pioneer Industries;

– Stub-meter, developed by Stanford Research Institute.

The state-of-the-art of non-destructive testing of adhesive bonded metal joints has already been well established: a report (prepared by H.F.L.Pinkney and R.F.Scott) was presented in February 1967 by the National Aeronautical Establishment (Canada), to the AGARD Structures and Materials Panel, on the investigation carried out by seven countries.

Other investigations were made by different experimenters, among which are H.M.Gonzales and C.V.Cagle at the Hughes Aircraft Company, V.H.Boruff of the Martin Company, Baltimore, R.E.Clemens of the Norair Division, Northrop Corporation of Hawthorne, G.B.Evans of Hawker Siddeley Aviation Ltd.,

Based on the results of the various investigations carried out on a large scale, the following conclusions can be drawn:

1. All of the three instruments are able to assess (only on a central area relative to the probe diameter) the cohesive, but not the adhesive strength of the bond.

2. The degree of adhesion cannot be expected to be shown by instruments based only on change of frequency or damping from induced vibrations.

3. For good accuracy and reproducibility it is essential to properly calibrate the instruments against a series of samples of known bond strength, prepared under the same conditions of surface treatment, adhesive thickness and cure parameters.

4. Provided the joints are dried, "no bond" can be established both in metal-to-metal or metal-to-honeycomb; thus, all dangerous bond degradation during service will be detected.

Instruments are hand portable and in most cases inspection can be carried out from the outside of the aircraft joint skin; suspected areas will be indicated by a light or sound signal.

4. 3 Ultrasonic Impulse–Echo Method

This method has been used for many years for flaw detection in casting and welding inspection, using various designs of probe with different angles of incidence to excite longitudinal, transverse, surface and plate waves.

The author was told that the instruments of this type currently used for metal-to-honeycomb panels are the following, but some other instruments are equally suitable:

– Echoskop MPR 105, by Lehfeldt;

– Metalloradar RV 5 and 6, by Réalisations Ultrasoniques;

– Sonoray, by Branson Instruments.

Of these three instruments, the author noted that, for the inspection of honeycomb panels, at Breguet Aviation, Biarritz, the Metalloradar was adopted. This instrument, like the other, is based on the principle of ultrasound reflection at discontinuities, porosity, and adhesive thickness variations.

The quality of the joint is determined comparatively from the waveform on the cathode ray tube; as the interpretation of the results is rather difficult (particularly in the event of many elements), very skilled personnel are required.

To ensure a quicker and more reliable inspection a sophisticated method (using longitudinal waves with 0.5 MH and sometimes 0.25 MH frequency and a single transmitter/receiver crystal) has been set up. This is based on two instrument settings, one for detecting and the other for identifying the type of defect (these are classified from N. 1 to 7 for sandwiches with up to three sheets per side).

Regarding the Sonoray, which operates also on the pulse-echo principle, the results are the following (as reported by Pinkney and Scott):

"On bonded specimens, the difference in the shape of the pulse decay cycle, displayed on the screen of the oscilloscope, was used to measure bond differences. In most cases, the void gave a shorter time pulse than the standard bond. However, the opposite was true in a few samples".

A special Perspex block which houses both a transmitter and receiver 5 MH crystal of lead zirconate titanate was developed at AID Laboratories for inspecting aluminium alloy honeycomb panels. The axes of incident and refracted bearing are inclined at an angle of 13° and 30° to the normal, respectively.

If adhesion is good only a small proportion of the incident energy is reflected, due to attenuation, and a larger signal is obtained. Defective areas could readily be detected from the differences in the amplitudes of signals received from sound and unbonded regions.

4.4 Acoustic Methods

A practical method of bond testing consists in tapping lightly the surface of the joint by a coin or pencil with hardness lower than the metal sheet. the clear difference of sound between the good adhesion area and the defective area can be heard. The usefulness of this method seems to be limited to the detection of area of no adhesion. Of course, skilled personnel are required; when the skins are thin the utmost care must be exercised.

The so-called method of "acoustic energy emission" consists in listening to the sound generated into the material when the bond is put under stress. It is a method still under study (Pollock effect observed with adhesive bonds); stress may be applied mechanically or thermally and the equipment consists of transducer, amplifier and a recording or counting system. The method lends itself to the inspection of large and complicated structures (with overlaps, angles, fillets, etc.) with no need for scanning. There are, however, some limitations to this method among which are the difficulty in locating poor bonds in a large structure, the necessity of putting the bond line under stress and accurate operator interpretation.

4.5 Depression Cup Method

The method consists in the local application of depression on the facing skin of the honeycomb panel, by means of a vacuum cup provided with a comparator for measuring the deformation caused by a pressure differential at the centre of the area under test. By this method unbonded areas can reliably be detected in panels with facing sheets less than 8/10 mm in thickness.

4.6 Radiographic Inspection

Radiographic inspection is used in production to check for defective adhesion of honeycomb to honeycomb and of honeycomb to skin, as well as defects of shape.

In the case of a curved panel, the tube focus must be placed in the centre of curvature of the panel. Radiographic inspection is also useful when doing maintenance work, not only in order to detect such defects as are perpendicular to the honeycomb facing sheets but to check for the possible presence of trapped water.

4.7 Thermal Methods

These methods are based on the heat transfer principle, unbonded areas acting as an effective barrier to heat flow.

Various kinds of equipment have been developed for detecting voids and areas of no adhesion on adhesive-bonded aluminium alloy components and aluminium alloy honeycomb panels.

The Thermal Bond Tester, developed at AID Laboratories, measures the normal deflection of the face when heated and seems to work quite satisfactorily (W.Thompson and A.T.Josling, AID Report NDT 1712, Jan, 1964). Voids and areas of defective adhesion affect the flow of heat and differences in the local surface temperature result. These are easily detected by means of infrared radiometers, even on rough and irregular surfaces.

Special infrared detectors are reported to sense very small surface temperature differences on surfaces slightly above room temperature, but the author has not seen any of these extremely sensitive devices.

4.8 Temperature Sensitive Coatings

Thermosensitive coatings which have sharp melting points or change their colours on reaching certain temperatures have been employed to inspect adhesive bonding. Cholesteric liquids (derivatives of cholesterol) possess the remarkable property of a fast response to temperature variations; for example in less than one second they change in colour from red to blue.

The visualization of voids and laminations is made possible by the poorer heat conductivity of the defective areas and the resulting slower increase of local temperature. Further evaluations should be carried out to establish the sensitivity of available devices to various types of flaws in different sandwich combinations.

5. INSPECTION OF WELDED JOINTS

5.1. General

The inspection methods used for welded joints are selected according to the kind of material, the welding process and the shape and thickness of the material.

Generally speaking, while all possible internal and external defects - peculiar to a given material, process or joint geometry - must be detected in production, maintenance inspection will only require the detection of cracks, which are often open at the surface.

Of course, when there are weld seams accessible on both sides the use of magnetic particle or penetrant liquid methods for detecting surface cracks is recommended in addition to other inspection methods such as radiography or ultrasonics.

According to the shape, the thickness and the type of the material to be inspected, as well as the degree of accessibility (which are so variable in aircraft structures), either the radiographic or the ultrasonic method is used; in certain instances (primary components or critical areas) both methods are employed.

5.2 Radiographic Inspection

The radiographic method is the most suitable for the inspection of spot-welds in heat-treatable light alloys containing appreciable percentages of alloying elements such as copper or zinc, widely used in aircraft structures.

In fact, the X-ray technique not only permits the detection of internal defects (such as cracks, splashings, porosities, blowholes, inclusions etc.) but also reveals the shape and size of the fused nugget shown by a dark ring - on which the mechanical strength of the joint depends.

The equipment and the operating techniques to be used should, however, be such as to ensure particularly high sensitivity, e.g. in the case of the most important structures of small thickness (0.8 to 1.4 mm total thickness), for which the current X-ray inspection intended to detect lack of fusion requires voltages of 15 to 25 kV.

Cracks in *butt welds* can be parallel or normal to the longitudinal axis of the bead and are easily detected only if their direction happens to coincide with the main beam of radiation. Sometimes cracks start from areas of lack of fusion along the angled wall of the bevel.

Care should be taken in the interpretation of radiographs, since cracks may not be detected even with good radiographic techniques.

When carrying out *in situ* radiographic inspection it is often impossible to place the film against the structural part that is presumed to be defective; a loss of sharpness results which, however, does not affect the detectability of fine cracks provided the geometric unsharpness (or penumbra) ranges from 0.003 in. to 0.007 in. (according to AID experience).

X-rays are not considered to be suited to the inspection of *fillet welds* which are more efficiently tested by ultrasonic waves.

Stereoscopic radiography *in situ* is often necessary in order to distinguish chromate paint or sealant cracks in thin components from shallow cracks in the metal: tube shift should be long enough.

5.3 Ultrasonic Inspection

Ultrasonic examination of butt welds, including flash butt welds, and T-joints from one side have found more extensive application for *in situ* inspection after the angle probe and oblique beaming were developed.

Moreover, the use of higher frequencies and focusing probes is predictable in order to improve the inspection accuracy on thin welded structures.

For detecting two-dimensional defects (such as lack of fusion and cracks) the use of transverse waves is usually preferable, since fine cracks are likely to escape notice when longitudinal waves are used.

Spot-welds in heat-treatable light alloys (total thickness greater than 2 mm) were inspected with a double probe (transverse waves) using a Metalloradar RV at 5 MH.

According to the results so far obtained by the International Institute of Welding in a research on correlating radiographic images and ultrasonic indications, this method will only indicate substantial differences in weld nugget diameter.

The author was told that spot-welded wing-tip tanks of aluminium alloy were successfully inspected with longitudinal waves by RTD, Rotterdam, using a Krautkrämer USIP-10 W tester equipped with a SMB 12 transducer at 12 MH.

By observing the number of reflections and their decay it is possible to distinguish a non-bonded spot from a 50% and 100% bonded one, provided uniform and satisfactory contact can be maintained.

Research work was carried out by the Technical High School, Hanover, under contract from Rolls Royce Ltd., in the field of in-process testing of spot welds on aluminium alloys, titanium alloys and nickle-base alloys.

Using the transmission technique (at frequencies of 2.5 and 5 MH) and ultrasonic transducers incorporated in the electrodes of the welding machine, the following conclusions were reached:

(1) On aluminium alloys the ultrasonic wave transmission improved as the nugget size decreased from an over-heated spot to a stuck weld.

(2) On the contrary, on titanium alloys the ultrasonic wave transmission improved as the nugget diameter increased.

(3) On nickel base alloys no observable difference in the ultrasonic wave transmission was noticed.

These inconsistent results may be due to several factors such as the grain size of the fused central area, the extension of the fused peripheral zone with dendritic structure; the area of contact between electrode tip and sheet indentation.

The need for further investigations into the capability of ultrasonics to meet the requirements of spot-weld testing appears obvious.

6. INSPECTION OF RIVETED OR BOLTED JOINTS

Ultrasonic flaw detectors are now widely used to check for cracks and/or corrosion in the lower skin under the overlap on fuselage or wing joints, making any dismantling unnecessary.

When areas of suspected weakness are not accessible to direct visual examination (such as a corroded interface in a lap joint) ultrasonic techniques can do the job both quickly and satisfactorily, provided the parts concerned lend themselves to this type of inspection.

6.1 Ultrasonic Inspection of Faying Surface Corrosion

On certain civil aircraft having wing plank splices ultrasonic inspections are required in order to detect interface corrosion.

Longitudinal waves at 5 MH are used, with a 1/4 in. lithium sulphate transducer: in the absence of corrosion the energy of the ultrasonic beam will dissipate gradually; if corrosion is encountered at the faying surface the signal will be greatly reduced by the accumulation of corrosion products and the scope will show a rapid decay.

It should be remembered that ultrasonic inspection indications are influenced by the tightness of fasteners (lower energy absorption at higher pressures), the faying surface sealant and by humidity (due to the coupling effect).

6.2 Ultrasonic Inspection for Cracks

Cracks on radius in plank splice configurations are satisfactorily detected using shear wave transducers at the most suitable angle (generally 70° for thin outer skins).

Cracks having a depth equal to half the skin thickness in the lower skin of fuselage riveted joints can be easily detected, from the outside by giving the Perspex probe shoe the local contour of the fuselage.

Different kinds of equipment may be used, for example a Krautkrämer USIP-10W at 4 MH with a MWB probe.

Care must be taken to calibrate the equipment with a test specimen representing the type of joint to be inspected and the defects expected.

6.3 Eddy-Current Inspection of Holes for Fasteners

The eddy-current method is recommended for detecting and measuring cracks in the holes of fasteners and bolts; these areas are extremely difficult to inspect by other techniques, such as penetrant liquid or ultrasonic waves, in the event of contamination.

A suitable bolt hole probe (single or double coil) is placed perpendicular to the inner surface of the hole to be scanned, to achieve high resolution.

Changes in the impedance of the coil, which is supplied with alternating current of suitable frequency, are analyzed by an electronic circuit. The suppression of the "lift-off" effect and other undesirable signals is ensured by modifications to the circuit.

Once the probe has been properly balanced, the walls of the hole can readily be inspected by rotating the probe and watching for a sharp needle deflection on the micrometer as the sensing coil passes over a crack.

Test blocks containing holes with natural or atificial cracks will be needed in order to determine the sensitivity of eddy-current tests.

The equipment generally used in Europe is the Defectometer 2154 (manufactured by Institut Dr. Foerster, Reutlingen, Germany), especially developed for crack detection and crack-depth measurement.

One of the advantages offered by eddy-current methods is the capability of detecting cracks even when covered or filled with dirt, oxide and other foreign matter.

6.4 Ultrasonic *in situ* Inspection of Critical Steel Bolts

Certain critical steel bolts (such as the ones installed in landing gears) can be inspected *in situ* by means of longitudinal ultrasonic waves to detect cracks starting on the radius under the head.

Three locations are scanned, keeping the axis of the transducer perpendicular to the surface of the bolt head, i.e. near the center hole, at the radius position and at some distance towards the periphery.

7. DISCUSSION AND RECOMMENDATIONS

When examining the various problems involved in the inspection of structures the available techniques have been compared and the methods which are now the most reliable will be indicated. In this final section some data on the further development of equipment and proposals concerning the need for research will be discussed.

Concerning the inspection of *adhesive bonding* it should be noted that variations in adhesive strength at the interfaces are not detectable: this is a gap which must be urgently bridged.

Research on the adhesion of epoxy resin lap joints has commenced at AERE, Harwell, the work being divided into the following sections:

- Study of the acoustic modal spectra of the bond.

- Theoretical model of the elastic behaviour of the bond.

- Electrical analogue of the bond.

- Study of the elastic anisotropy in the bond, using high frequency ultrasonics.

It is hoped that a better knowledge of the vibrational properties of the bond will permit the prediction of the total strength (i.e. adhesive plus cohesive strength).

Fokker (Schiphol) have a test instrument under development which should be able to measure electronically the surface properties of the joint area before bonding.

The Fokker Bond Tester is being developed for:

applications on new materials and structural configurations such as stainless steel, fiberglass reinforced plastic, titanium, boron-fibre composites, new adhesives, brazing metals;

automation of equipment, high-speed testing, facsimile recording, high sensitivity for light weight sandwich structures (i.e. for space applications).

At Rolls-Royce, Derby, a radiopac penetrant is used for inspecting new materials of low X-ray absorption, such as carbon fibre resin composite; radiographic sensitivity is considerably improved.

A further point which must be considered concerns the need for research on spot-weld inspection by means of ultrasonic techniques, particularly on titanium alloys, stainless steel and nickel-base alloys. There are now different opinions as to the actual capability of ultrasonic inspection techniques under various operating conditions because of the lack of basic knowledge of the effect of many factors involved.

The problems of ultrasonic inspection acceptance standards - for the evaluation of type, size and location of possible discontinuities - should be approached on the basis of their predictable effects on service behaviour.

A suitable classification of categories of joints and components to be inspected, based on their structural or functional importance, should be worked out.

Service experience with modern airliners has shown that, even adopting adequate inspection plans, carried out with the most appropriate procedures, unfortunately it is not always possible to prevent fatigue failures on some highly stressed components, such as main landing gear bogie beams.

New methods to detect fatigue cracks at a very early stage should be tried by laboratories in possession of the equipment required (e.g. IABG, München).

Special birefringent coatings and fatigue life gages to be applied on critical areas of components being tested offer some promise.

Other lines of possible research and development in the detection of fatigue crack initiation might be, as envisaged by R.S.Sharpe, the method of acoustic energy emission (see section 4.4) and a method based on detecting and counting the electrons emitted when fresh surfaces are produced.

Some metallurgical properties of materials (such as the amount of residual austenite and very small amounts of secondary phases in stainless steels) might be detected, this again is Sharpe's opinion, by a new non-destructive technique based on the absorption of the recoilless nuclear resonance of gamma rays (Moessbauer effect).

But in the near future it is unlikely that equipment based on such principles and permiting the above examinations will be manufactured.

The author believes that a handbook of recommended procedures for the non-destructive inspection of typical joints and components used on aircraft structures would be very useful and should be compiled as soon as possible.

Concluding this report the author proposes that a body consisting of a few experts of non-destructive techniques, selected in the NATO countries, should be set up. These specialists should undertake the task, with the co-operation, if possible, of the best non-destructive research centres.

Another basic task of the body should be the study of the best way to improve the human aspect of NDI activities, namely the training of inspectors for various techniques on a standardized international basis.

SELECTED REFERENCES

(No specific correlation is made with the text of the report)

1. McMaster, R.C. — *Non-Destructive Testing Handbook.* Ronald Press, New York.

2. Müller, E.A.W. — *Handbuch der zerstörungsfreien Material-prüfung.* Oldenbourg, München.

3. Krautkrämer, J.H. — *Werkstoffprüfung mit Ultraschall.* Springer, Berlin, Göttingen.

4. Betz, C.E. — *Principles of Penetrants.* Magnaflux Co., Chicago.

5. Doane, F.B., Betz, C.E. — *Principles of Magnaflux.* Magnaflux Co., Chicago.

6. Sharpe, R.S. — *A Review of Bond Testing Techniques.* 5th Annual Conference on Adhesion and Adhesives, London, April 5, 1967.

7. Sharpe, R.S. — *Recent Developments in Non-Destructive Testing.* Pergamon Press.

8. Sharpe, R.S. — *The Physicists' Approach to Non-Destructive Testing.* The Institute of Physics and the Physical Society, September 1964.

9. Sharpe, R.S. — *Research in Non-Destructive Testing.* British Journal of NDT, March 1967.

10. Sharpe, R.S. — *The Development of Flaw Detection Techniques at Harwell.* International Atomic Energy Agency, Vienna, 1965.

11. Cotterel, K., Sharpe, R.S. — *The Use of Carbon Tetrachloride as a Radiopac Penetrant.* NDT, July/August 1962.

12. Sharpe, R.S., Aveyard, S. — *The Inspection of Thin-Walled Stainless Steel Reactor-Grade Tubing.* Journal of the Iron and Steel Institute, October 1963.

13. Sharpe, R.S. — *Diagnostic for the Engineer.* New Scientist, 2 February 1967.

14. Sharpe, R.S. et al. — *A Quantized Eddifax Technique.* Ceramic Division, Atomic Energy Research Establishment, Harwell, 1966.

15. Thompson, W., Spear, J.A.N. — *An Ultrasonic Method of Detecting Area of Non-Adhesion in Aluminium Alloy Honeycomb Panels.* AID/TN, November 1964.

16. Fleming, D.J. et al. — *An Assessment of Radiography for the Inspection of Aircraft Structures.* AID Report, December 1960.

17. Thompson, W., Senior, H.A, — *A Non-Destructive Test for Adhesive Bonded Fibreglass - Aluminium Alloy Joints.* AID Report, March 1965.

18. Thompson, W., Thacker, H.J.T. — *Non-Destructive Testing of Metal-to-Metal Adhesive-Bonded Joints and Adhesive-Bonded Honeycomb Panels.* AID Report, November 1961.

19. Thompson, W.., Josling, A.T. — *A Non-Destructive Test for Adhesive Bonded Joints.* AID Report, January 1964.

20. Rockley, J.C., Best, P. — *An Assessment of the Use of Radiography in the Determination of Bore Eccentricity in a Hollow Piston.* AID Report, September 1966.

21. Best, P., Rockley, J.C. — *A Radiographic Method for the Inspection of Faulty Cable Connectors.* AID Report, January 1967.

22. Pinkney, H.F.L., Scott, R.F. — *Data from Non-Destructive and Destructive Tests Carried Out in a Program to Evaluate Ultrasonic Devices for the Inspection of Adhesive Bonds.* NRC of Canada, February 1967.

23. Schliekelmann, Rob J. — *Quality Control of Adhesive Bonding Metal-Structures.* Aircraft Factories Fokker, Schiphol, Amsterdam.

24. Evans, G.B. — *The Fokker Bond Tester.* Sheet Metal Industries, October 1965.

25. Gonzales, H.M., Cagle, C.V. — *Non-Destructive Testing of Adhesive Bonded Joints.* Fourth Pacific Area National Meeting of ASTM, Los Angeles, October 4, 1962.

26. Clemens, R.E. — *Evaluation of Fokker Bond Tester Systems.* SNT Technical Meeting, Los Angeles, February 13, 1962.

27. Miller, N.B., Boruff, Von H. — *Adhesive Bonds Tested Ultrasonically.* Adhesive Age, June 1963.

28. *Contrôle par Ultra-Sons des Assemblages Métalliques Collés.* Breguet Aviation.

29. *Contrôle Periodique des Elements Métalliques Collés.* Breguet Aviation, February 7, 1966.

30. Bodet, M. — *Les Collés dans la Construction Aéronautique.* January 31, 1967.

31. Lo Pilato, S.A., Carter, S.W. — *Unbonded Detection using Ultrasonic Phase Analysis.* Material Evaluation, December 1966.

32. Botsco, R.J. — *High Resolution Ultrasonics.* Material Evaluation, April 1967.

33. Botsco, R.J. — *Sonic Resonator.* Materials Evaluation, November 1966.

34. de Sterke, A. — *Weld Inspection by Ultrasonic Waves.* Materials Evaluation, January 1964.

35. Gallinaro, P. — *Radiographic Inspection of Spot Welds in Primary Aircraft Structures.* Rivista Italiana della Saldatura, Novembre-Dicembre 1962. (Translation 3207 - The Central Technical Information Service, Friars House, London).

36. Woodmansee, W.E. — *Cholesteric Liquid Crystals and their Application to Thermal Non-Destructive Testing.* Material Evaluation, October 1966.

37. Harting, D.R. — *The S/N Fatigue-Life Gage: A Direct Means of Measuring Cumulative Fatigue Damage.* Experimental Mechanics, February 1966.

APPENDIX

ORGANIZATIONS VISITED

The following is a list of the organizations that were visited while conducting the European portion of the survey of the NATO countries. The names are shown in the order in which the visits were made.

1. AIR FRANCE. Diréction du Matériel, Paris-Orly (France).
2. HISPANO-SUIZA. Division Après Vente, Bois-Colombes (France).
3. BREGUET-AVIATION. Biarritz (France).
4. BREGUET-AVIATION. Division Contrôle, Velizi-Villa Coublay (France).
5. DEUTSCHE LUFTHANSA. Materials and Process Engineering, Hamburg (Germany).
6. INDUSTRIEANLAGEN-BETRIEBSGESELLSCHAFT. München (Germany).
7. TURBO-MAN. München (Germany).
8. KRAUTKRÄMER. Köln (Germany).
9. ROYAL NETHERLANDS AIRCRAFT FACTORIES FOKKER. Schiphol (Holland).
10. ROYAL DUTCH AIRLINES. Engineering and Maintenance Division, Schiphol (Holland).
11. RÖNTGEN TECHNISCHE DIENST. Rotterdam (Holland).
12. ATOMIC ENERGY RESEARCH ESTABLISHMENT. Non-Destructive Testing Centre, Harwell, Didcot (United Kingdom).
13. AERONAUTICAL INSPECTION DIRECTORATE LABORATORIES. Harefield (United Kingdom).
14. ROLLS ROYCE. Aero Engine Division. Divisional Quality Engineer, Derby (United Kingdom).
15. BRITISH EUROPEAN AIRWAYS. Engineering Base, London Airport (United Kingdom).

SURVEY ON THE APPLICATION OF NON-DESTRUCTIVE INSPECTION METHODS TO COMMERCIAL AIRCRAFT, 1968-1970

by

Robert B. Oliver

CONTENTS

SUMMARY

A sampling of commercial airline overhaul bases, airframe manufacturers, research laboratories, and equipment manufacturers were visited. The objectives of these visits were to:

1. Evaluate the current experiences in NDI
2. Isolate the best NDI procedures
3. Make recommendations to improve the accuracy of the methods and to stimulate development of improved methods.

Individual reports for each facility visited are submitted in the Appendix of this document.

Three conclusions are obvious; the state-of-the-art is adequate for cost effective inspection of commercial aircraft, the inspections are standardized throughout the world, both by the manuals issued by the manufacturers of the airframes and by the national and international codes, and there is good communication between the inspection organizations of all the major airlines.

The preceding paper by Ing. P. Gallinaro, presents a slightly different viewpoint from the present one.

SURVEY ON THE APPLICATION OF NON-DESTRUCTIVE INSPECTION METHODS TO COMMERCIAL AIRCRAFT, 1968-1970

Robert B. Oliver

1. INTRODUCTION

Generally, Non-Destructive Testing and Inspection involves diagnostic techniques based on experience, employing the measurement of any physical or physical-chemical phenomenon that can be correlated to the desired functional or performance characteristics of the end product. The property or attribute being measured may not in itself be critical but is one which can be correlated, through functional or destructive tests, with the specified product characteristic. The available methods are primarily indirect and usually must be tailored to the specific problem, considering size, material, shape or configuration, and orientation with reference to accessible surfaces. It is seldom the case that one method is adequate for a complete inspection or evaluation. While one method may be optimum for inspection of a specific characteristic, supplemental methods may be required for the other parameters. In nearly all cases, a correlation study of non-destructive and destructive test results will be needed, and a valid calibration standard must exist.

Actually, non-destructive methods have value much greater than simple quality control inspection. Many of these methods have the capability to assess the physical properties of the material and to reveal the adequacy and constancy of the processes. In all cases, development of non-destructive techniques must run concurrently with the development of the materials and processes they are intended to control. The development must consider the probable modes-of-failure, attributes to be evaluated, calibration and correlation of associated equipment, and the fabrication of reference standards. Since the non-destructive techniques are dependent on the materials of construction (or combination of materials) and shape or configuration, the specific technique selected must be optimized for each application.

During the past twenty-five years there has been an accelerating growth of the applications of NDI methods. We can expect this growth to continue. Most of the growth has been prompted by specific problems. Many of these problems have been solved with commercially available equipment by ingenious design of inspection tooling, and some have required considerable imagination in finding measurable attributes from which can be inferred characteristics that are not directly measurable. During this same period there has been a great advance in all sciences, many of these discoveries have the potential of being developed into new and powerful NDI methods. The various government agencies could profitably invest funds in basic research to define the applicability and the advantages and limitations, thus supplying the users on non-destructive testing with the data to apply the new physical measurements to solve timely testing and inspection problems.

The state-of-the-art of non-destructive testing has been reviewed by several groups in recent years with the conclusion that the state-of-the-art, as known to a relatively small number of experts, is far more advanced than is generally realized by the technical community of the world. The solution of this problem is obviously a better distribution of the vast amount of published information and an increased educational effort. There is a vast amount of literature in both English and German and a report NMAB-252, issued by the National Academy of Science Materials Advisory Board (American), has a section listing professional societies, handbooks, periodicals, and information centers that should improve the dissemination of the current state-of-the-art knowledge.

The biggest problems in applying non-destructive methods are accuracy, reliability and reproducibility. There are many reasons to want NDI methods to be quantitative but, since these methods are comparative, indirect, and very sensitive, it is extremly difficult to design a test to give absolute values accurately. Also, the methods generally are affected by properties and attributes other than the one that is being measured.

These are the reasons that the development of any non-destructive test procedure must parallel the development of the part or process that the test is to evaluate and control. This way the manufactured reference standard can be designed and fabricated so that it has all of its properties the same as the object that is to be inspected and so that other variables do not affect the measurement of the prime variable. For example, a reference standard for an ultrasonic test must have the same surface finish, the same unit attenuation, and the same propagation velocity as the parts to be inspected. In addition, during this development the correlation between the instrument readings, referenced to the calibration standard, and the results of functional or destructive tests can be correlated and a calibration for the property or characteristic being measured can be established, taking into account the statistical variability of the tests that are being correlated.

2. GENERAL

The problem of analyzing the state-of-the-art of non-destructive testing and the need for improvement and development is complicated by the variety of applications. The needs are distributed over three general areas, each having a different type of problem and a different incentive to use these valuable methods.

Research, Development, and Design of structures or assemblies require evaluation of materials, and the monitoring or control of processes. This inspection effort is directed toward insuring that the samples, assemblies, or structures to be tested by the research or design engineer represent a statistical family to permit design evaluation and decision. The emphasis is more on the measurement of properties and evaluation of materials than on the detection of flaws. In this environment the inspection is performed by people with a high technical competence and generally the cost is not a controlling factor.

Manufacturing is aimed at building an assembly to designs and to specifications that have been proven and qualified during development. The kind and amount of testing is prescribed by the design engineer in cooperation with the stress analyst, reliability engineer, and the quality assurance analyst. The amount of testing specified is generally a compromise of the probability and cost of failure with the cost of the inspection. Also, in the aircraft industry the manufacturer specifies the inspections that will be used by the operating companies in their maintenance and overhaul programs.

Maintenance and Overhaul performs the NDI prescribed by the manufacturer in the maintenance and overhaul manual for the particular aircraft. Generally the inspection procedure is also prescribed, and the manual may be revised as operating experience dictates. The maintenance and overhaul organization may perform additional inspection at their option or as unusual operating incidents may indicate the need. The operating organizations are under the greatest economic pressure to minimize the amount of inspection. Not only do the inspections cost money directly but they decrease the time that the aircraft can be in revenue producing service. On the other hand, the cost of failure of an aircraft while in flight is very great. Management can be sold on added inspection in the overhaul base only if the inspection reduces overhaul costs or fulfills a demonstrated need for safety and reliability. Management has a difficult decision balancing the total cost of inspection against the potential cost of failure of an aircraft in flight.

3. EVALUATION OF CURRENT EXPERIENCE

As a result of good communications between the various manufacturers and the operating airlines and between the many airlines, non-destructive testing is well standardized. The survey revealed numerous cases of one airline discovering a new problem and developing equipment and procedures to inspect for the new problem. This information was immediately transmitted to the govenmental agencies and to the manufacturers of the aircraft. The information was then evaluated and transmitted to all other lines operating that type of aircraft. In cases where the defect is recurring and experienced by all operating airlines then the special fixtures and probes become commercially available. This is illustrated by the problem of cracking in the first stage rotor in a jet engine; in 1968 the overhaul bases were using home-made wooden fixtures to handle the eddy-current probe and by 1969 the overhaul bases were using commercially manufactured metal fixtures.

Landing wheels are inspected at all overhaul bases, with eddy-current methods being widely used though ultrasonic methods were also observed. The selection of ultrasonic methods is based generally on the accessibility of the probable defective condition, since direct probe contact is needed for the preferred eddy-current inspection. Both methods are adequate and quantitative but the eddy-currents require direct access. The current trend in wheel inspection for aircraft with multiple wheeled gear is to evaluate the severity of cracking rather than to scrap a wheel. The objective is to balance the economics of risk of failure of an individual wheel and the cost of a new wheel and to establish predictive criteria for allowable crack size with low failure risk.

Corrosion of the skin on the underside of the fuselage of aircraft results from the collection at the low point of condensate and leakage from all sources. Eddy-current and ultrasonic methods have been used to measure the degree and distribution of corrosion attack. To some extent the selection of method is one of personal choice. The eddy-current method is more dependent on alloy composition and heat treatment, but it will detect intergranular attack as well as pitting type corrosion.

The ultrasonic method can be more accurate for the measurement of corrosion thinning and evaluating pitting but it is relatively insensitive to intergranular attack. Light weight, battery-powered instruments are now available that have digital read-out and can accurately measure sheet thickness down to 0.010 inches (0.25 mm) to an accuracy of 0.0001 inches. These instruments will replace the older, resonance type instruments.

Landing gear structures are critical and these are inspected principally by ultrasonic methods. These inspections are well standardized for aircraft that have been in service long enough to have established modes-of-failure.

Honeycomb structures are inspected by radiographic and ultrasonic methods. The radiographic inspection detects accumulated condensate and evaluates the integrity of stiffeners and doubler. The ultrasonic methods primarily evaluate the integrity of the coverplate bonding.

Generally, current experience in the commercial aviation industry is adequate for the problems encountered in commercial aircraft operation. The quality of inspection is uniform on an international basis due to well established channels of communications. The controls imposed by the national and international aviation agencies force the reporting of defective conditions and the maintenance and overhaul manuals are constantly being revised as the need is indicated by these reports. New problems and new methods are discussed at least annually at the meetings of the International Air Transport Association.

4. ISOLATION OF THE BEST PROCEDURE

This is not a realistic goal since selection of methods and specific techniques or procedures is dependent on equipment availability and in some cases it is influenced by personal choice. In addition, for commercial operations much of the inspection is prescribed in detail by the manual for each model of aircraft. If we interpret "procedure" as the NDI method, then the task will be more difficult because the methods are not generally competitive but are complementary, or in many examples two or more methods may be needed. An example may be the detection of cracks in window frames: radiography is commonly used for screening because it is the most economical method, but an ultrasonic method is much more reliable for the detection of tight cracks oriented at random angles to the surface. Technically, eddy-current or ultrasonic procedures are more reliable crack detection procedures than are radiographic methods, but either method requires direct access to the inspection surface and requires tools or fixtures to position and align the probe. The selection of a method or procedure is based on accessibility to one or both surfaces and on the availability of proper tooling; an example is the inspection of the rivet holes in the in-board panel of the 707 wing for fatigue cracks. All rivets are removed and eddy-current probes of the proper sizes for the holes are used to scan around the inner surface of each hole in the panel and in the wing structure. At other locations in the structure it is not feasible to remove the rivets so eddy-currents cannot be used, but special ultrasonic shear-wave probes are designed to direct the beam tangential to the hole and under the head of the fastener.

If we assume that "procedure" means the step-by-step operation of a specific method for a particular part for a particular flaw or characteristic, then the best procedure is the one that has been correlated with the proper destructive tests, is used with automatic or semi-automatic scanning equipment, and is instrumented so as to require the minimum of operator control and interpretation. An example may be the inspection of the wing skin for corrosion pitting on the inner surface.

An ultrasonic scanning system is available that holds on to the wing surface with suction cups and automatically scans an area of about six square feet at each position and records areas of skin thickness less than the present value.

Further improvements can be made in the inspection procedures by the incorporation of computer or logic devices into the instrument systems. One example is an eddy-current inspection system for small diameter tubing that incorporates a small computer that can be programmed to make accept/reject decisions on the basis of flaw size, location, and frequency. Another example is an ultrasonic system to evaluate forging billets. The pulse-echo ultrasonic system sends signals to a computer memory during the scanning of each billet, and at the completion of the inspection the computer prints out a quality rating for each billet. The use of well designed scanning equipment and the incorporation of data processing and data analysis or correlation accessories greatly improve the speed, accuracy and reliability of the inspection. It is obvious that such procedures require a large investment and can only be justified by a large volume of similar parts.

The best assurance that the optimum technique is used for a particular problem is to have a competent engineering staff. Then they must be given adequate facilities and access to the advancing technical knowledge.

5. RECOMMENDATIONS

The *first recommendation* is that the Base Management must employ a supervisor of the Non-Destructive Inspection who is experienced and knowledgeable in the field and who is ingenious and innovative. The knowledge developed over the past twenty-five years is well documented in English, German, and Japanese, and to a lesser extent in French, Italian and, Spanish. The supervisor should be familiar with these sources of information and with the equipment available, both in the past and at the present time. Also the Base Management must pay the operator/inspectors for a sufficiently high skill that the techniques and methods will be used in a manner to give reliable and accurate measurements.

The competent supervisor will insure that the operator/inspector is well trained, that he works with effective and proven procedures and instructions and that calibration or reference standards are available for each specific inspection. It is imperative that NDI personnel be subject to the same disciplines as other quality control personnel including training and qualification testing for each piece of equipment used and for each procedure.

The *second recommendation* is that the management of the NDI function at each Base insist that calibration standards are developed for each method and that the development is a joint effort of the aircraft manufacturers and all overhaul bases. These standards must be proven as representative of the structure to be inspected and can then serve to insure an accurate and correlatable inspection. In addition, the data from all sources must be analyzed to evaluate the limits-of-error inherent in the procedure. These data, in turn can be used to evaluate the competence of each inspecting organization and can be used to evaluate proposed, improved techniques.

The *third recommendation* is that funding be secured for Interdisciplinary Laboratories to continue effort on partially solved, or unsolved problems. The following list of problems has been suggested by numerous study groups and committees in the past:

(1) Surface cleanliness and measurement of adhesive strength.

(2) Early or incipient fatigue damage.

(3) Methods for the wide variety of composite materials.

(4) Methods specifically for non-metallic materials.

(5) Methods to measure residual stress.

The *fourth recommendation* is that the NDI personnel be sponsored by their employers to participate in technical society activities and that they also actively participate on the NDI Committee of the Aircraft Industries Association. Perhaps AGARD could exert influence to make the AIA more truly an international organization. If this can be accomplished, this is the organization that should write a Handbook on Aircraft Inspection.

APPENDIX

FACILITY SURVEY REPORTS

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APPENDIX

FACILITY SURVEY REPORTS

COMPANY: Air France, Direction du Materiel, B. P. 120, Orly Aérogare (94), France
CONTACTS: Mr Moulin, Mr Paul Geriment, Mr Gandin

Basic Business

Maintenance and overhaul of the current fleet of 707's, 727's and Caravelles. In future they will also service the 747, Airbuses, and the SST's. They also perform overhaul, on a contract basis, for other lines flying into Orly.

Personnel and Training

An ample supply of personnel appears to be available and the company maintains good training programs. Supervision is very competent.

Equipment

Radiography - Portable units for use on installed assemblies and for inaccessible areas of the airframe, stiffeners, doublers, and other highly stressed members are radiographed, princibly to detect cracking: also window frames. In addition, inaccesssible areas of the airframe are radiographed to detect indications of corrosion.

Magnetic Particle

Separate facilities are available for magnetic parts, one in the engine overhaul area and the other for airframe components. Control of process is maintained with steel strip specimens coated with a brittle electroless nickel plate which is subsequently cracked.

Penetrant Inspection

For parts made of non-magnetic materials two facilities are available: one in the engine overhaul plant and the other in the airframe area. The process control is standard.

Ultrasonic

Contact ultrasonics are used on a wide variety of parts. The Metalloradar unit is equipped with a variety of transducers and an extensive assortment of wedges and shoes is available to fit the transducers to the many shapes of parts to be inspected. Typical assemblies and parts are landing gears, other forged parts, and wheels including braking areas. Ultrasonics are used to detect cracking in window frames that are missed by radiography.

Eddy-Current

Förster Model 2154 Defectometer with an extensive assortment of probe coils. Major use is to inspect bolt and rivet holes for cracking, with specially designed probes for each type and size of hole. This method is the basis for the "707 wing life extension program". Turbine blades are inspected for cracks on the leading and trailing edges with special probe positioning fixtures. Eddy-currents are also used for crack detections in the brake disks and as a supplement to several of the ultrasonic inspections. They are introducing eddy-current evaluation of the heat-treat condition of rivets to eliminate the splitting of over-aged rivets.

Procedures

The aircraft users are bound by the procedures issued by the aircraft manufacturers; however, these can be amended or upgraded by the user if he finds the need for improved testing or if he wants to work to tighter standards. Conformity to the manufacturer's standards is monitored by the national (and international) agencies.

Problems

Detection and evaluation of corrosion attack under protective coatings, at faying surfaces and in inaccessible regions. Also needed is detection of incipient fatigue prior to readily detectable crack formation.

COMPANY: Deutsche Lufthansa, Overhaul Division, Hamburg-Flughafen, West Germany
CONTACTS: Ing. Gert-Nagel, Ing. Lothar Schickert

Basic Business

Maintenance and overhaul of the current fleet of 707's, 727's and Viscounts. In the future they will also handle the 747 and the Concordes. The base at Frankfurt handles most of the maintenance but all overhaul is in Hamburg, both power plant and airframe. They also perform contract overhaul and modification for other airlines flying into Germany.

Personnel

Engineering staff appears very competent and the inspection force is well trained and guided by a complete set of formal procedures. Deutsche Lufthansa operates an extensive training school for all crafts and skills.

Equipment

Radiography. Müller, Andrex, and Federex portable equipment for use on installed assemblies and for inaccessible areas of the airframe. Also used to monitor corrosion in inaccessible locations on the Viscount.

Penetrant. Extensive use of penetrant inspection of disassembled engine and airframe parts. Extensive facility to handle large parts with partial mechanization of the test procedure. Field inspection of nosewheel landing gear for the 737 until reliability rating can be established. First stage blades for Pratt and Whitney engines have the penetrant inspection applied while the blade is cantilever loaded in a special fixture.

Magnetic Particle. Wilhelm Tiede equipment and supplies used on all stressed parts.

Ultrasonic. Krautkrämer equipment (contact techniques) with large assortment of transducer probes. Large assortment of transducer wedges to adapt the transducers for inspection of specific airframe parts. Used to inspect highly stressed areas of landing gear components, high strength bolts and fasteners, parts of hydraulic cylinder, and landing wheel, including the braking areas.

Eddy-currents. Förster Model 2154 Defectometer with an extensive assortment of probe coils. Major use is to inspect rivet and bolt holes for cracks, with specially designed probes for each size and type of hole. This inspection is the main method for the "707 wing life extension program". Turbine blades are inspected using special probes to position the coil on the leading and the trailing edges. Also a special fixture with a shielded coil is available to inspect the first stage turbine wheel for cracks without removal from the engine.

Procedures

The aircraft user is bound by the procedures issued by the aircraft manufacturer; however, these can be amended or upgraded by the user if he finds the need for improved testing or if he cares to work to tighter standards. Conformity to all standards is monitored by both national and international aviation agencies. Lufthansa generally operates to tighter NDI standards than those prescribed.

Problems

Detection and evaluation of corrosion attack under protective coating, at faying surfaces and in inaccessible regions. Also need for detection of incipient fatigues prior to readily detectable crack formation.

COMPANY: Alitalia, Aeroporto Fiumicino, Rome, Italy
CONTACTS: Ing. Costa, Ing. Pallavicini

Basic Business

Maintenance and overhaul of the commercial fleet. A new hangar is available to service the Boeing 747, the air buses, and supersonic transports. Alitalia also provides contract services for other airlines landing in Rome.

Equipment

The laboratory was well equipped and included capabilities to calibrate pressure gages, load cells, torque wrenches, and other measuring devices. Portable equipment is available to be used on the aircraft in the hangars.

Eddy-current equipment and special probe coils, similar to those in other overhaul bases, were in use to detect fatigue cracking in wing panels and to check turbine discs for fillet cracking.

Personnel were well trained and worked in conformity with the standard procedures in the overhaul manual.

The calibrated load cells are used to determine the center of gravity of the aircraft periodically.

Problems

NDI applied to airframe is standard, involving radiography of structural assemblies and low-energy radiography and ultrasound for corrosion. New campaign to check wheels since all airlines are showing an increased incidence of wheel cracking. Eddy-currents used extensively to check leading and trailing edges of blades and vanes for cracking. Also, remotely manipulated eddy-current probes are used to check the condition of several of the compressor wheels. They are also using radiography to check the clearance between the blades and nozzles. Isotope radiography is used to inspect burner cans and transition ducts. They have found several cases of burner can failure on the Rolls-Royce Conway engines; in one case the flame had burned through one spoke in the engine support ring. They have found several cases of severe sagging of the transition duct between the cans and the nozzle entry vanes on the Pratt and Whitney engines used for the DC-9.

The radiography of the engines in place to examine the burner cans and ducts is unique. Rather than use the long source/object and short object/film distance they use an approximately equal distance, selecting the ratio to enlarge and blur the overlapping details and allow viewing the desired can or duct section.

COMPANY; British European Airways, Heathrow Airport, London
CONTACTS: Mr A.R.Bond, Mr P.M.Brown

Basic Business

Maintenance of the fleet of aircraft; Comets, Viscounts, Vanguards, and Tridents. It is interesting to note that there are no Boeing or Douglas aircraft in this fleet.

Equipment

This base has a greater emphasis on radiographic and eddy-current methods than seen previously. The film handling equipment is unique; all film is in prepackaged rolls. The film is cut to length and handled in single, long lengths rather than loading into several cassettes. The film, after exposure, is processed in the full length, then viewed and stored in rolls. This approach deserves some consideration by any radiographic operation. Projection enlargement is used in viewing X-ray films for images with fine detail. The eddy-current instrumentation for skin thickness, and wheel and brake disk inspection were either home-made or home-modified commercial equipment.

Problems

Thickness of the skin of the fuselage is measured to determine amount and distribution of corrosion. These data are analyzed to predict remaining life and determine optimum time to replace the skin.

Eddy-current methods are used to detect and evaluate cracking of landing wheels, both aluminum and magnesium. This program is determining allowable crack size to permit safe-life rather than fail-safe policy. All small cracks so located are recorded and monitored at each maintenance cycle.

BEA was the only overhaul base to express an interest in applied residual stress measurement. Also, they appeared to be making more studies of cost of inspection versus tangible savings.

COMPANY: Breguet Aviation, Biarritz (Anglet and Parme), France
CONTACTS: Mr Piquepe (Head, QC), Mr Hericourt (QC-Anglet)

Basic Business

Aircraft structures, including part or all of the airframe for the Mirage III, Jaguar, Fokker F-27, and BR-1150S. Fabrication of honeycomb panels is also part of the effort in the plant at Anglet.

Personnel and Training

Employment is stable in the Biarritz area so a large and continuing training program is not needed. Inspection procedures are extensive and complete. Also, as the fabricator of the airframe (or component), the procedures become part of the maintenance manual for each aircraft.

Equipment

Radiography facilities for film radiography are available and the facilities for image-tube fluoroscopy will be installed in the near future. The major use of radiography is for the evaluation of honeycomb panels for splices of the honeycomb, crushed core, and similar accidents in fabrication. Radiography is also used for the inspection of weld joints in metallic ducting and piping.

Magnetic Particle

Most parts using MPI are bought on vendor certification so most MPI effort is for monitoring sample lots or for special problems.

Ultrasonic

The bulk of the ultrasonic inspection is used to inspect resin-bonded honeycomb structures or resin-bonded metal-to-metal lap joints. The Fokker Bond Tester is used for metal-to-metal resin-bonded joints for bond integrity. Pulse-echo (Metalloradar) ultrasound is used to inspect the resin bonding of metallic face plates to metallic core.

Eddy-Current

Two models of the Permascope (Manufactured under license by Fischer in Stuttgart) are used to measure coating thickness. One model measures nonmagnetic coatings on ferromagnetic bases and the other is for nonmetallic coatings on nonmagnetic base material.

Equipment is available in the laboratory to verify alloy and heat treatment and to check for thinning due to corrosion.

Microwave

X-band microwaves to evaluate quality and performance of radomes.

Origin of Procedure

As prime fabricator the methods and procedures are generated in the Quality Control department. The reference and calibration standards are of two kinds: examples of defective components or assemblies and items in which known defects have been purposefully introduced during their fabrication.

Problems

A better method is needed to inspect resin bonded phenolic-to-phenolic joints.

A faster method to inspect honeycomb panels.

A method to determine strength of bond non-destructively.

COMPANY: MAN Turbo, 8 München-Allach, West Germany
CONTACT: Dipl. Ing. Dickhaut

Products

Turbine engine parts and subassemblies

Personnel

Stable employment and good training program.

Very good QC procedures and documentation.

Equipment

Magnetic Particle. Much mechanization. Magnaflux and Wilhelm Tiede materials supplied by Magnaflux and Tiede. Trying new orange colored particles. Very bright.

Penetrant. Magnaflux and Wilhelm Tiede.

Radiography. Müller (Philips). Very well planned facility, wire type penetrameter. Experimented with color radiography, wide latitude but lower contrast.

Eddy-current. Very little.

Ultrasound. Krautkrämer immersion (laboratory model) used principally to inspect turbine wheel forgings prior to machining.

Procedures

Internal, written to conform to customer specifications. Procedures and criteria rigidly enforced. Excellent MPI and Penetrant standards. Ultrasound standards are drilled holes and natural defects in rejected parts.

COMPANY: C.M.F.Müller GmbH, Hamburg 1, Alexanderstrasse #1, West Germany
CONTACTS: Dr Ing. Rudi O.Schumacher, Mr Andreas Opeldus, Mr Adolf Pflug

Basic Business

Manufacturing X-ray machines and X-ray inspection systems. They are leaders in constant potential X-ray machines, followed by Siefert in Germany and Picker in the United States. They also produce the direct imaging X-ray inspection system (Searchray). As part of the Philips organization this company sells on a world-wide market. Müller produces a high gain image amplifier system for fluoroscopic inspection.

Equipment

The standard X-ray equipment is extensively used in the aerospace industry for a wide variety of inspection operations. The Searchray employs a special television system with a Vidicon camera tube that is sensitive to X-rays and directly forms a television image without first forming a light image. Because the Vidicon tube is sensitive to only low energy X-ray photons, the applications are limited to thin sections but the system is very sensitive and versatile.

Müller (Norelco) produces a complete line of X-ray diffraction, X-ray fluorescence, and electron microscope equipment.

Problems

Improving sensitivity and image sharpness for image tube fluoroscopy. Developing a direct imaging Vidicon tube that is responsive to higher energy X-rays and is a more efficient photo-electron converter.

COMPANY: FIAT, Turin, Central Research and Control Laboratories, Motors and Aviation, Nuclear (Sorin), Italy
CONTACTS: Dr Galotto, Dr Magistralli, Dr Walther

Basic Business

Fiat is known primarily as an automobile manufacturer, but the company is also active in aerospace and nuclear research. The aerospace manufacturing is to both FIAT design and on various licensing arrangements on an international basis.

Equipment

The Central Laboratory at Miafiori serves not only the automotive division but also provides technique development for other divisions. The efforts at the Motor and Aviation Division were directed to airframe structures and turbine engine parts. There were facilities for magnetic particle and penetrant inspection and a new immersed ultrasonic inspection installation. Also, in addition to the standard X-ray facilities, there was a mechanized fluoroscopic unit for the rapid inspection of brazed turbine nozzles.

At the nuclear reactor site (Sorin), there were several beam tubes devoted to testing and inspection problems including neutron radiography.

Problems

Most of the problems did not require new approaches but rather required tools and fixtures to position complex parts for inspection. Novel programs at the reactor facility included low-angle neutron scatter and neutrons radiography of castings. Dr. Walther has data indicating correlations between low-angle neutron scatter and early fatigue damage. The neutron radiographic program will start with castings such as automobile engine blocks, to determine feasibility and cost.

COMPANY: Hispano-Suiza, 92-Bois Colombes, Paris, France
CONTACTS: Mr Norbert Litwin, Mr Ladoux, Mr C.A.J.Mounard

Basic Business

Turbine engines and landing gear assemblies. Turbo-engines for stationary power plants (Nordberg) and the Rolls-Royce Tyne engine. Landing gear for the Caravelle and the Concorde. Previously famous for piston engines and machine guns. They are now part of the SNECMA organization.

Personnel and Training

There was no opportunity to objectively evaluate the competence of the personnel or the scope of the training program.

Equipment

Radiography, magnetic particle, and penetrant: Standard practices.

Ultrasound: both the Krautkrämer and Metalloradar equipment are used. Prototype parts receive intensive inspection to determine the areas of a part or assembly that require inspection and to establish the needed frequency of inspection. Principal applications are to landing gear parts: hubs and spindles, brake disks and highly stressed linkages and devices.

Eddy-current: used principly for the wheel hub areas but also as a supplement for the ultrasonic inspection.

Origin of Procedures

As a primary supplier of parts and assemblies the procedures are generated in the Central Laboratory and the Quality Control Department. The procedures are incorporated into the Maintenance and Overhaul Manual.

Problems

No problems were defined.

COMPANY: Industrieanlagen Betriebsgesellschaft, Ottobrunn bei München, Einsteinstrasse, (Portal-8000 München 33 Schliessfach 505) West Germany.
CONTACTS: Dr Ing. T.Gaymann, Dr Ing. Knorr

Basic Business

Full scale structures testing and analysis. Government sponsored Research and Development laboratory with major part of funding supplied by the West German Government. Principal efforts are directed to full scale structural testing of aircraft (static and dynamic).

Personnel

Superior research laboratory type technicians.

Equipment

Wilhelms Tiede equipment for MPI and Penetrant Inspection, minor effort: Radiography: Müller and Fedrex equipment, minor effort. Ultrasonic: Krautkrämer equipment (contact), minor effort. Eddy-current: Förster Model 2154 Defectometer, used for crack detection and crack depth determination.

Procedures and Criteria

Because this is a testing installation, very little of the NDI is aimed at field inspection; their interest is rather in the evaluation of materials and structures. There is a strong interest in measuring residuals stress and determining progress of corrosion. In this area they use X-ray diffraction and X-ray fluorescence analyses.

Problems

Methods to detect early fatigue damage, determine magnitude and direction of residual stress, and to determine strength of brazed or adhesive bonded joints.

COMPANY: Atomic Energy Establishment, Harwell, England
CONTACTS: Mr Roy Sharp, Mr McEachern

Basic Business

The centre has two functions: one is to compile and publish the world-wide literature on NDI and the other is advanced research and development in non-destructive testing. With the markedly reduced budget they have an intensive program to secure industrial sponsorship.

Current Laboratory Programs

Their most spectacular presentation was true ultrasonic holography. They are using a focused transducer and a special filter to get parallel beam transmission and a point source receiver; thus the returning ultrasonic signal is nearly coherent. The reference beam is synthesized electronically and the ultrasonic signal and the reference signal are multiplied in real time and the product is recorded on a single facsimile recording. The recording is photographically reduced and the three-dimensional image is reconstructed on an optical bench with laser illumination. The 35mm transparency contains all of the ultrasonic information from a 3 in. x 5 in. x 2 in. object.

There is an ultrasonic goniometric project to study surface stresses and elastic properties at the surface. This technique involves measuring the reflected ultrasonic beam as a function of reflected angle. They observe positive-going signals at the critical angles for longitudinal and shear wave propagation and a strong negative-going signal for surface wave propagation (Rayleigh trough). These signals contain complete information on the elastic properties at that point and a potential correlation with residual stress as measured by X-ray diffraction.

A third major project is high resolution radiographic equipment. The electron beam is pulsed and focused similarly to the beam in an electron microscope, giving an X-ray source size on the target in the order of a few microns. This minute source size permits projection enlargement of the image and extremely fine image resolutions. Current equipment is limited to 40 kV but equipment is being constructed for operation at 100 kV. The new equipment will permit precision radiography of welds in thin sections of aluminum and titanium.

COMPANY: Dr J.ü.H.Krautkrämer, Gesellschaft fur Electrophysik, 5 Köln-Klettenberg, Luxemburger Strasse 449, West Germany
CONTACTS: Dr H.Krautkrämer, Mr Karl-Georg Walther

Basic Business

Development and manufacturing of ultrasonic inspection equipment and systems. The products of this company are marketed on a world-wide basis and are highly competitive, even in the United States.

Personnel and Training

The research and development functions are staffed with competent Scientists and Engineers under the direction of Dr. J. Krautkrämer. The manufacturing personnel appear to be excellent craftsmen judging from the quality of the products. All of the marketing personnel are competent specialists in ultrasonic inspection.

Equipment

The company manufactures a number of models of ultrasonic instruments and a wide range of probe types to meet the needs of the general market. In addition they make custom instruments for special inspection problems. They also design and market material handling systems to provide high speed reliable inspection of various mill products such as pipe, sheet and plate.

Other Activities

Krautkrämer conducts training programs to educate the users of ultrasonic equipment in both the United States and Germany. They publish a journal, "The Echo", in both English and German, which reports on techniques for ultrasonic testing.

The field service personnel are readily available also to assist in writing procedures for specific ultrasonic inspections.

Problems

The Krautkrämer laboratories have explored the applications of ultrasonic wave propagation to the measurement of residual stress. They have been successful with artificially stressed samples in the laboratory but they do not think the method will work for parts in service.

They have placed a strong emphasis on the calibration of the instrument and the transducer (probe) to improve the quantitative evaluation of flaw size. They also developed the DGS Diagrams to improve the inspectors' capability to assign a quantitative value to each detected flaw.

COMPANY: Branson Instrument Company, Progress Drive, Stamford, Connecticut 06904, USA
CONTACTS: Mr John Bobbin, Mr John Oliano

Basic Business

Development, design and manufacture of ultrasonic equipment. The instruments are marketed under the trade names: Sonoray, Vidigage and Digital Caliper.

Personnel

The engineering and field service personnel are very competent and inventive.

Equipment

The Sonoray series of instruments are pulse-echo type flaw detectors. They are wide band instruments and the model 600 is of modular design with a wide range of special function modules available.

The Vidigage (and Audigage) are resonance type instruments used primarily for thickness measurement.

The Digital Caliper (Models 101 and 102) are pulse-echo ultrasonic thickness gages. The model 102 has three ranges (0.010 to 0.100; 0.050 to 1.000; and 0.20 to 10.00 inches) with a 0.1% accuracy. This instrument should have application to corrosion surveys of thin sections. Easy to calibrate, since they are linear over a wide thickness range.

Problems

Quantitative determination of flaw size, correcting for variability in ultrasonic velocity and attenuation in the test material.