Non-Destructive Evaluation (NDE) and Aircraft Availability

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1.0 INTRODUCTION

The issue of aircraft availability has been a problem for air forces for many years, however it has come to prominence in recent years largely because of the intense pressures on military budgets. Decreasing procurement and operational budgets require the utmost in efficiency from the forces to offset the limited numbers of aircraft which can be afforded. Non-Destructive Evaluation (NDE), also widely known as Non Destructive Testing (NDT) and Non Destructive Inspection (NDI), can play several roles in increasing aircraft availability, although if not correctly incorporated into the aircraft's overall life management plan the potential benefits may not be realised and NDE may be perceived as contributing to the availability problems.

In this paper the role of NDE in aircraft life management will be reviewed briefly, emphasising the developing roles for NDE in operating new and ageing legacy systems. Examples of improvements to NDE capability will be given showing how, by making NDE more practicable they enable reductions in aircraft downtime, allowing greater availability. Optimisation of inspection strategy will also be discussed and suggestions for future employment of NDE as a basis for prognostic health management allowing increased use of condition based maintenance (CBM) will be discussed.

2.0 NDE AND AIRCRAFT LIFE MANAGEMENT

Aircraft and component lifing can be based on several philosophies:

- **"Safe Life" –** The aircraft life is fixed by a major airframe fatigue test. In principle there should be no requirement for NDE during the aircraft safe life, after which it ought to be scrapped.
- **"Damage Tolerance"** – The life is determined by calculation using assumed initial defects and estimated growth rates. This usually involves the use of NDE at set periods to verify that no defects greater than the initial size are present. In principle the process can be repeated as often as required, although in practice other factors, particularly the changing distribution of anticipated defects, limit the life which can be obtained.

- **"On Condition" -** Components are inspected periodically and used until a defect is encountered (also known as Retirement for Cause).

Different nations and services use a mixture of these approaches, for example the USAF use damage tolerance for platforms and increasingly favour on condition for components, the USN and UK use safe life for airframes. Safe life also predominates amongst European nations who make their own equipment (e.g. France, Germany, Italy) but damage tolerance is adopted by operators of US equipment (e.g. Netherlands, Belgium).

NDE is an integral part of the damage tolerance and on condition approaches. Although it should not be required in principle for a safe life aircraft, NDE is used on all aircraft types within the safe life period. The requirement for NDE may arise from experience with the major fatigue test, from fleet experience or from changes in operating conditions. Increasingly as aircraft approach the end of their safe lives, there is a pressure to extend the life to save replacement costs. This often increases the NDE requirement as the airframe and components are effectively being operated on a damage tolerance or on condition basis after the safe life is exceeded.

In "new" systems the use of NDE would tend to reduce availability as it requires aircraft downtime and is likely to encounter only sub-critical indications which may require further action. The use of NDE may not be included in initial planning and the need to use NDE may be deferred by replacement of items. Preventive maintenance is more aimed at the long term so it is not driven by actual defects, hence there is limited scope for NDE to reduce the maintenance undertaken and the ensuing cost.

In "ageing" systems, NDE may be the only viable way to keep the systems flying, hence ***any*** system availability depends on NDE. In these systems NDE reduces an otherwise prohibitive preventative maintenance burden by targeting corrective repair action and avoiding the cost of unnecessary replacement or refurbishment.

The changing, generally ageing, aircraft population with the greatly increased emphasis on reduced maintenance and support costs has lead to a changing role for NDE. It was traditionally used primarily to ensure safety and to investigate "incidents" such as minor accidents or airframe overstress. Its roles in aircraft lifing were, periodic, programmed inspections as part of damage tolerance lifing, ad hoc usage to reinforce safe life where hot spots or changes in usage occur and to allow "on condition" life for specific components.

More recently NDE is increasingly being used to support life extensions replacing safe life with damage tolerance/on condition lifing, to replace or reduce other forms of preventive maintenance and to enable use of CBM.

3.0 NDE RELATED COSTS AND COST SAVINGS

In aircraft maintenance there is a very often a decision to be made, whether to inspect, refurbish or replace. Replacement or refurbishment at a pre-set airframe life have often been favoured by aircraft operators as "Terminating actions". They eliminate follow-up costs of further inspections for a further predictable life interval, but the up-front cost may be considerable.

Inspection will in turn lead to:

1) No action (usually);
2) Repair or refurbishment;
3) Replacement.

The initial costs are those of the inspection rather than the follow-up action which hopefully can be avoided or considerably deferred in most cases.

The decision on whether to inspect or implement a pre-determined terminating action will nowadays usually be an economic one, which is most affordable, often considering mainly the short term.

Although one of the most obvious costs in using NDE is the cost of the extra equipment required, NDE equipment is not usually a major cost. Simple instruments cost from $5k while many systems cost from $20-200k. These costs are enough to limit the use of NDE in some industries, but are usually insignificant compared to the overall support costs of military aircraft. NDE systems costing more than this have usually failed to sell. Large installations however can be costly, but can often be justified on an individual case basis, where there is sufficient throughput of work (see examples below).

A greater inspection cost is the manpower required. This can add up to a significant cost, although still only a small part of the total maintenance burden. In the present circumstances where recruitment and retention of personnel are often problematic the number of posts rather than the actual cost may be an issue. Training and Certification are also a growing concern.

The cost of additional aircraft downtime, especially preparation for the inspection, is often the main cost. Clearly increased aircraft downtime reduces availability and increases the required fleet size. The time required to prepare an aircraft for inspection very often exceeds the inspection time, sometimes by an order of magnitude or more.

In order to increase the scope of reliance on NDE to cut overall maintenance costs and improve availability, there are several challenges which are directing current NDE research and development.

Inspection of a greater percentage of airframe would expand the opportunities for CBM. This requires the development of NDE techniques capable of increased speed for large areas of accessible structure and improved penetration into the structure for inaccessible areas or components. It also requires extension of inspection capabilities and understanding, especially where complex geometry and multi-layered structures complicate inspection practices.

Increasing inspection intervals clearly offers the opportunity to cut inspection related costs. More importantly, however, if increased inspection intervals are compatible with major servicing intervals there can be a dramatic reduction or even elimination in the overhead costs of aircraft downtime and preparation. Increasing inspection intervals can be achieved by using inspections capable of determining improved detail allowing smaller defect threshold to be used, increasing the warning period. The most effective scheduling of inspections would be enabled by incorporating inspection fully into a prognostic predictive framework.

These improvements to inspection capability and strategy should help to improve acceptance of NDE by aircraft operators. To ensure this, it will be necessary to overcome any negative impact on aircraft availability, to demonstrate minimised overall maintenance cost through efficient use of depot inspection and to demonstrate the impact on the structural integrity management of the fleet.

4.0 IMPROVEMENTS TO NDE METHODS

Improvements to NDE for use in the above situations, particularly the ageing systems, includes increases in sensitivity, speed and access capability. These improvements can be made in some cases by adopting radically new methods, but often evolutionary development of existing methods can bring about the necessary increase in capability, particularly when the recent improvements in computing power and automation are utilised.

Traditional inspections by the use of methods such as Ultrasonics or Eddy Current were originally devised for much more limited applications. They operate by scanning a small probe over the area or features of concern. While they are ideal for limited area inspection, they are relatively slow, require intimate access to the flaw location and are usually only semi-quantitative, often defects are not even “sized” by the primary inspection requiring follow-up investigation of any indications. They can be greatly improved by incorporation into scanning systems, either manual or automated, particularly for inspection of large areas. This gives better detail of damage, allows data storage and retrieval for record-keeping allowing improvement in data fidelity. It can also reduce manpower requirements, both by reducing the time required for manual manipulation of the probes and by reducing the necessary operator skill levels.

Further improvements to traditional methods have involved the development of multiple array probes using many parallel channels to allow more rapid scanning. Incorporation of automated data analysis allows rapid, real-time analysis of the huge data sets generated and allows more sophistication, provided the presentation is simple. Fully automated, dedicated systems based on these improved traditional methods minimise manpower requirements while allowing routine 100% inspection.

Examples of systems adopted by the UK and US Air Forces include:

- **Ultrasonic Inspection of Composite Structure for BVID.** Ultrasonic scanning with a greater rate of data acquisition through the use of a wide array probe greatly reduced inspection times, mapping damage using a manual scanning system. Inspection of a fighter sized wing (Harrier II/AV8B) using a single element hand held probe required 6 days, the use of a 16-element array reduces this to 5 hrs.
- **Automated Scanning System (MAUS).** A further step in improved inspection appropriate for large structures is a portable automated scanning system which attaches to the aircraft skin. It can carry out raster scans without supervision and can be used with various NDE techniques including Ultrasonics and Eddy Current. The system features automated setup and data processing, it is currently used for corrosion detection on KC135, B52, and E3 aircraft.
- **Engine disk inspection systems.** Larger fixed automated scanning systems are appropriate for inspecting large numbers of complex components. Robotic eddy current inspection systems enabled a Retirement For Cause strategy to be used for F-100 engine disks which otherwise had an unacceptably short fatigue life. Periodic inspection allowed the component life to be doubled with an estimated cost saving of $850M. Further improvements and savings are projected under the Engine Rotator Life Extension (ERLE) programme.
- **Robotic Radiography – MAX** (Multi-Axis X-ray). Recently, the USAF the commissioned a dedicated, automated digital X-ray system enabling inspection of the complete F15 empennage for corrosion by a gantry robot. The initial costs were justified by expected labour savings over an existing manual task of $200k-$300k per year. Additional benefits include elimination of chemical film processing, increased operator safety, real time processing and live image examination eliminating the need for multiple shots.
- **Dedicated Fastener Hole inspection systems.** Fastener holes have long been recognised as initiation sites for fatigue cracking. In one example of this, the C130 wing centre section was found to suffer from hidden cracking around fasteners, and there were several hundred fasteners which would have required inspection. (Similar problems affect commercial aircraft). The original inspection required removal of the fastener to allow insertion of a rotating probe eddy current scanner, but this was not

viable for the large numbers of fastener sites. Eddy current systems were developed using rotating probes or multi-element arrays which could inspect the holes without prior removal of the fasteners. These systems reduced inspection time to seconds per fastener, measuring defect angle, size and depth. A Magneto-Optic Imaging system was developed for more rapid inspection of a limited area. Although less sensitive than the eddy current instruments it is claimed to be around 20% more rapid, and with no requirement to locate the fasteners which are imaged automatically, it can be used to inspect through paint or surface coatings.

The above examples all show how conventional NDE methods can be transformed to make them compatible with the new requirements. A lot of work has also been done to develop new techniques based on imaging rather than scanning technologies for the inspection of large areas. The principal techniques investigated have been:

- Thermal Methods.
- Pulsed Thermography.
- Lock-in Thermography.
- Sonic IR / Thermosonics.
- Optical Methods.
- Holographic Interferometry.
- Electronic Speckle Pattern Interferometry (ESPI).
- Shearography.

A further group of techniques which have been used for structural monitoring of large areas are:

- Acoustic Methods.
- Guided waves.
- Acousto-ultrasound.
- Acoustic Emission.

These techniques all seek to cover large areas quickly, but have severe limitations in the degree of detail and /or thickness of structure which they can cope with. They have therefore been limited to niche applications

Thermal methods have very limited penetration into monolithic structures, especially if they are electrically conducting with a consequently high thermal conductivity. They have been used successfully for inspection of lightweight structures, including space structures, where they have been introduced for leading edge inspection on the space shuttle. Thermal methods are useful for locating disbonds, in one example the German Air Force developed a thermographic technique to detect disbonding of engine intake heater mats. Thermography has also been used in production inspection of components including GRP helicopter rotor blades.

Optical methods are similarly limited in their penetration into structural materials. They have been used mainly for production inspection of thin skinned sandwich structures.

The acoustic methods have very different limitations, being most suitable for inspection of large, heavy weight, thick section structures. The guided wave method is now routinely employed in inspection of pipes and storage tanks, but it does not have the resolution to be used for large area inspection in complex airframe structures where there are too many features to perturb the guided wave pulses. Guided waves can however propagate through structure to hidden elements. Techniques to inspect internal structures from outside using waves guided by the structure have been used in nuclear reactors. This concept formed the basis for a technique using creeping waves which was used for inspections of C141 Weep Holes and C130 Spar Caps. This technique reduced the time required by 40-50hrs by eliminating disassembly.

Acoustic emission has also been used successfully in simple, heavy structures. Despite persistent attempts and continued development it is has not been possible to use it in aircraft applications due to the difficulty in distinguishing defect-related acoustic events from background structural noise.

Alternative methods to improve access to structures include the use of NDE probes or imaging systems on endoscopes, this has been done with digital cameras, laser ultrasonics and eddy current probes. Robots and permanently installed sensors have also been used for specific applications.

5.0 INCORPORATION OF NDE INTO SYSTEM LEVEL LIFE MANAGEMENT

Simply applying a periodic inspection solution leaves several potential problems. The inspection interval has to be set, but it is not always compatible with the maintenance schedule. Reliance on NDE implies that the reliability of the inspection determines the safety level, hence the reliability of the NDE technique must be assessed. “Unanticipated” corrective maintenance can be very expensive in terms of aircraft availability, therefore the value of NDE will be greatly increased if it can be used for prognostics, predicting faults at an early enough stage that corrective action can be planned within normal maintenance tasks rather than taking the aircraft out of service.

The inspection interval is determined by the defect growth rates and damage tolerance of the structure, the minimum detectable flaw size and the reliability of the inspection methodology, technique, and operator. The viability of an NDE solution may depend on whether the inspection interval can be fitted into the maintenance programme, for example the VC10 transport specified a 6 year requirement for corrosion detection while civil aircraft typically have a 5 to 8 year repaint schedule.

NDE Reliability is often described by Probability of Detection (POD) curves. In Damage Tolerance lifing, only the characteristic defect size $a_{90/95}$ is used. In situations where this appears inadequate, more efficient interpretation of the NDE reliability can give improved performance estimates. In principle, an inspection can be chosen to match desired reliability with inspection interval and safety level. Currently accepted methodology only deals with simple POD depending on one defect size parameter, appropriate for fatigue cracks. There is no analogous standard approach for image data, especially where automated data analysis is used, which might be appropriate for corrosion detection.

A historical objection to NDE has been that it can reduce aircraft availability. Although the maintenance operations which will result from detection of defects by NDE can be foreseen, scheduling maintenance is difficult if an initial inspection is used to define the requirement or scope for further work. NDE would be much more valuable as a basis for preventive maintenance if it were used to give advance warning and to predict condition for a future safe operating period. This is the goal of prognostics.

Prognostics aims to predict future maintenance requirements through knowledge of the current state of a system and its future operations. Predictions of safe operating time and likely severity of future damage can be made from usage monitoring, structural health monitoring and/or NDE. It will be crucial to understand how uncertainties in current knowledge of the system condition propagate to give uncertainty in the future condition. Usage monitoring and SHM are both likely to be limited in the information they can give on the current damage state, although they may be used to direct inspections. NDE is limited by the precision of its measurements, but this can be measured. Remaining safe operating period and optimal corrective maintenance could be planned by using the NDE measurements of the existing condition as input to a defect growth model.

Using NDE in this way, operators can hope to improve CBM by predicting the future condition of the system, but the analysis has to specify what will go wrong and, crucially, when it will go wrong. The scope for savings and life extension could be impressive, for example the USAF Engine Rotor Life Extension programme (ERLE) projected doubling of engine component lives resulting in cost avoidance of $1.3Bn arising from just engine monitoring. NDE can be a major contributor to the gains by enabling prognostic health management, but the limitations of inspection must be well understood and reflected in the strategy.

6.0 CONCLUSIONS

Due to intense pressures to minimise ownership costs, NDE is being used in new ways. Some cost reduction associated with NDE arises from reductions in inspection costs due to the development of more efficient inspection systems. Greater savings can be expected to arise when NDE is used to enable efficient CBM strategies.

The main challenges to NDE are increasing the areas of platforms which can be inspected cost-effectively, this requires improved large area coverage methods and techniques which improve access.

More quantitative and more sensitive inspection methods may be required to extend inspection intervals and to allow prediction of safe operating periods by incorporating NDE into a prognostic health management approach.

In order to benefit fully from using NDE to improve maintenance, NDE with its benefits and limitations needs to be fully integrated into the overall system level life management strategy. NDE capabilities need to be built into the system model to make optimal use of the information NDE can supply as an enabling technology for life extension or condition based maintenance planning.