

AIRFRAME LIFE EXTENSION VERSUS RE-AIRFRAMING: ECONOMIC AND AIRWORTHINESS CONSIDERATIONS

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Abstract

This paper discusses the issues that need to be considered by operators and design authorities when rotorcraft airframes approach the original design service life. Older rotorcraft types often lack a rigorously determined safe life for the airframe, so on what basis can the nominal "service life" be extended? Attempts to extend service lives on the basis of fracture-mechanics-derived inspections have foundered due to rapid crack growth under rotorcraft load spectra. Residual strength to limit load (fail-safety) is often impossible to justify. However, history shows that airframe failures rarely, if ever, cause rotorcraft accidents, so is the expensive decision to re-airframe a fleet justifiable on airworthiness grounds? How does a rotorcraft type designed to the airworthiness codes extant 40 years ago measure up to today's requirements?

The economic argument has two facets: Firstly, manufacturing techniques have improved dramatically in 40 years and so it should be possible to design a cheaper to produce airframe. Airframe designs based on sheet metal fabrication have very high parts count and high direct labour content. It is possible to rationalise these designs as monolithic machinings or composite structures. The viability of recovering the non-recurring cost of the rationalised design is thus a function of the number of airframes being replaced and the degree to which the new airframe complies with the latest airworthiness standards. Secondly, as an airframe ages, its cost of ownership increases as both the corrosion resistance measures fail and fatigue cracks occur. The historical cost of maintaining an airframe can be misleading as the frequency of repairs will increase with time.

This paper discusses these issues, drawing on experience with two long-serving airframe types.

Introduction

The introduction of new rotorcraft types into civil or military service is becoming increasingly rare. This is due to a number of factors not least of which is the high costs of the initial design, development and service introduction. These factors often lead to new types being developed under large government sponsored international collaborative projects. These aim to address the needs of all the nations

involved. There are clearly risks that the resulting product may not exactly meet the needs of any of the participants and such projects often have very long gestation periods.

Also, comparative studies by WHL have shown that older types, designed to less onerous airworthiness requirements and fitted with simpler systems, often have a competitive advantage in terms of payload fraction. Among the design requirements that have become more stringent over time and that drive aircraft empty weight are crashworthiness, system redundancy, environmental operating envelope, crew comfort, damage tolerance, bird strike resistance, electromagnetic compatibility and fire resistance.

These factors force operators and design authorities to consider extending the life of their existing fleets. One example is the Westland Sea King. This is a derivative of the Sikorsky SH3/S61 family (designed initially in the 1950/60's) that entered UK MoD service in 1969. Sea King airframes are no longer in production. The projected UK out of service date for these aircraft, assuming that the life can be successfully extended, is now 2018 – at which point the aircraft will have been in-service for 50 years!

In contrast to Sea King, under the Future Lynx contract from the UK MoD, WHL are designing a replacement Lynx airframe. This is an improvement over the existing airframe in that it offers increased strength to permit a higher all up weight, improved crashworthiness and lower cost of ownership.

This paper uses these two airframe types to illustrate the factors relevant in the re-airframing-versus-life-extension decision making process. Throughout the paper, re-airframing is taken to mean replacing existing airframes with a completely new design rather than with a remanufactured one of the existing standard.

Definition of a Structurally Significant Item

The term Structurally Significant Item (SSI) is used throughout this paper and it is necessary to offer a definition. An SSI has been defined by WHL as “any detail, element or assembly that contributes to carrying flight, ground, pressure or control loads and whose failure could affect the structural integrity necessary for the safety of flight.”

A subtly different definition was proposed by MASAAG (Reference 1) as “a structural detail, element or assembly which is judged significant because of the reduction in aircraft residual strength or loss of structural function which are consequences of its failure”.

Either definition will suffice.

Basis of Airframe Lives

Older types such as the Westland Sea King, which was developed from the Sikorsky SH3, had an arbitrarily declared “service life” for the airframe. This had no basis either on test or by calculation, although some key airframe SSIs, such as the tail fold lugs, are lifed by local fatigue tests. This approach was considered acceptable for airframe items such as lift frames and longerons, where an alternative load path existed, on the basis that a failure could probably be tolerated under normal flight loads. Presumably, it was considered that by designing an airframe to static loads, the frequency of repair, and hence cost of ownership, would be satisfactory.

Nowadays, the aircraft designer must consider all areas of the rotorcraft structure for full fatigue substantiation. For a SSI to have no fatigue substantiation, it must be shown that it is not subject to significant fatigue loads. The aircraft designer has two main choices for fatigue substantiation: Safe Life or fail safe considering flaw growth. For fail safety to be declared, residual strength to limit load levels must be demonstrated.

This means that any item whose failure would reduce strength to below limit load is a SSI. This clearly has implications for older types when such rulings are imposed retrospectively. When an analysis of the Westland Lynx was done, using failed elements in the airframe finite element model, the number of SSIs increased from 8 to 29. To justify a life extension all SSIs must be evaluated.

Life Extension: Airworthiness Considerations

Full-scale Airframe Fatigue Test

One option for extending the life of an existing type is to perform a full-scale airframe fatigue test in order to demonstrate that a safe life beyond the declared service life is available. This is a slow and an expensive option. A full-scale airframe fatigue test will cost several million pounds and may take 6 years. An aircraft may well have to be taken from the fleet to provide the specimen. The lead aircraft in the fleet will probably exceed the declared service life well before useful results are obtained from the test. The extreme case of this would be for the test to finish after the out-of-service-date. It is unlikely that an aircraft type with an adequate safety record will be grounded whilst the test is “catching up” – in which case the benefit of the test must be queried. Some types may have been cleared by a previous fatigue test. If the test specimen and the test rig still exists it may be possible to recommission the test to increase the cleared life. Otherwise this particular option is not preferred.

Retrospective Application of Fail-Safety-Considering-Flaw-Growth

Another option for extending the life of an existing type is to retrospectively apply fail-safety-considering-flaw-growth principles to older airframes. That is to use fracture-mechanics-derived inspection intervals as the basis for life extension. If viable this would be ideal – the bulk of the work could be done analytically and relatively quickly. Once the airframe service life has been reached, if not before, a programme of rigorously determined inspection intervals is put in place to protect continued airworthiness. Reference 1 showed that this approach is not practicable because, by the time a crack is of a detectable length, it is growing very fast. Very short inspection intervals are predicted – typically 20 hours by NDT. Figure 1 illustrates a typical airframe crack growth prediction. This rapid crack growth is due to the fact that rotorcraft load spectra include high frequency, high R-ratio loads.

R-ratio is defined as the minimum stress in the cycle divided by the maximum stress in the cycle. Typical ground-air-ground cycles have low R-ratio values of 0 to 0.1 whereas for rotor passing cycles R is about 0.7 to 0.9. The threshold value of stress intensity, above which cracks grow, is an order of magnitude lower at these high R-ratio values than at R = 0.

Small flaws will start to propagate from industry standard initial flaw sizes (say 1.3 mm) under low frequency ground-air-ground and manoeuvre cycles. At relatively short crack lengths, that are only reliably detected by NDT (say 2 mm), high frequency rotor passing loads start to propagate the crack so that

the rate of crack growth accelerates. Other manufacturers have confirmed these conclusions. The difficulty in detecting such small flaw sizes is illustrated by Figure 2. This shows the flaw sizes and types that are detectable by various NDT methods.

Station 8875 Roof Frame Flange - Crack Growth Prediction

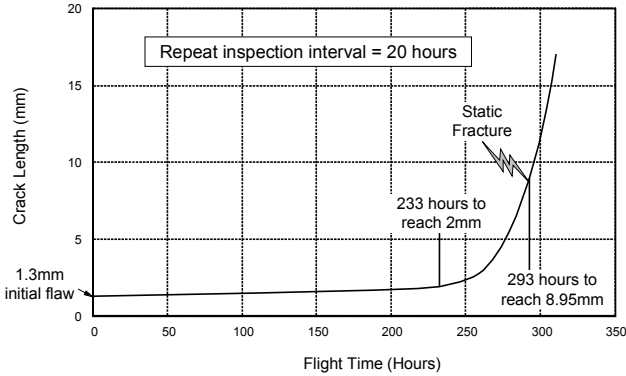


Figure 1 Typical Crack Growth Prediction

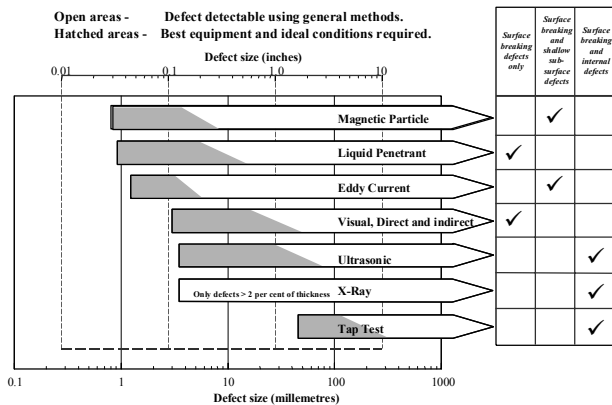


Figure 2 Flaw size detectability with various NDT methods

Fail Safety and Residual Strength

A refinement of the approach above would be to show that the airframe had limit load residual strength with a SSI failed. Of course, by the definitions given above, this would show that the item was not in fact a SSI! Visual (rather than NDT) inspections could then be used to detect complete failure of the SSI at an inspection interval set by either fracture mechanics or safe life principles with appropriately elevated loads in the alternative load path. However, finite element work done by WHL has shown that conventional metallic helicopter airframes, designed statically to ultimate load, may only have a residual strength of 75% limit load with key airframe SSIs failed. This approach can therefore also strictly be considered to be impractical although the examples given below show otherwise.

Sea King Frame 290 It is interesting to note that most Sea King aircraft have suffered cracking of the aft lift frame at Station 290. Failure occurs in five different modes as shown in Figure 3. Analysis would show that this reduces residual strength to below limit load but no catastrophic failures have resulted. The failure is well known by operators and is visually inspected for at an interval of 25 hours.

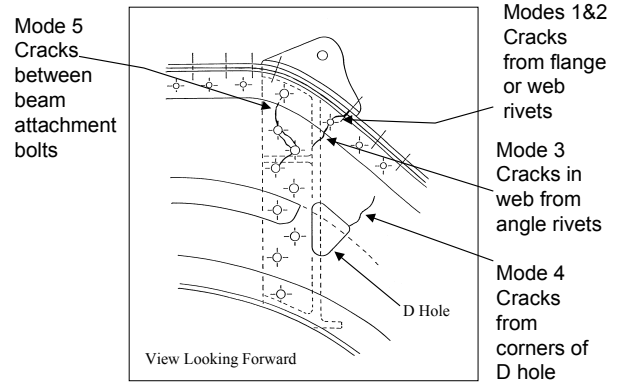


Figure 3 Sea King Frame 290 Failures

This practical finding perhaps illustrates that the flying of a manoeuvre that exceeds the residual strength, when there is a crack present, is statistically unlikely. However, a review of Operational Data Recording (ODR) measurements on the MoD Sea King fleet, showed that exceedances of 1.7g occurred 4 times in 89 hours of data. Although this g-level is a crude approximation of 75% of limit load, since it makes no allowance for aircraft weight or associated angular accelerations, it was more frequent than expected. As a consequence of this finding, Sea King aircraft with high operating hours now operate with a flight envelope restriction of 1.4g, that relates to the onset of perceptible G. This is intended to restrict the aircraft's exposure to manoeuvres that would exceed the residual strength were a crack to be present.

Lynx Rear Fuselage Early standards of Lynx airframes suffered a number of fatigue failures, especially in the rear fuselage and pylon. On later variants these problems were addressed by reinforcing design changes. However, despite the fact that the transport joint and the rear fuselage longerons were shown to be SSIs (again by using failed elements in the airframe finite element model and showing that the residual strength is only 75% limit) none of the failures caused incidents let alone catastrophic failures. On un-reinforced aircraft these areas are now subjected to regular inspections.

Airworthiness Changes

Modern techniques for static load case calculations use whole aircraft simulations to model the critical manoeuvres. For the Sea King it was hoped that, by applying such modern techniques, it could be shown that the original set of design loads from 1957 was conservative. If this were the case, a greater margin between residual strength and normal flight loads could be demonstrated. However, when shear force and bending moment envelopes were produced these showed two significant load increases. These increases were the result of different philosophies and resulted from both flight and ground cases. The traditional load case calculations never associated the maximum local normal acceleration with the maximum local mass, whereas the new “rational” methods always do. Figure 4 shows a typical bending moment envelope comparison from this work.

Fortunately, an analysis of rational gust cases showed that these were all below the substantiated envelope and within the fail-safe limits. This was just as well because it would not have been possible to set a practical flight envelope restriction to protect the airframe from limit gusts. This is also shown by Figure 4.

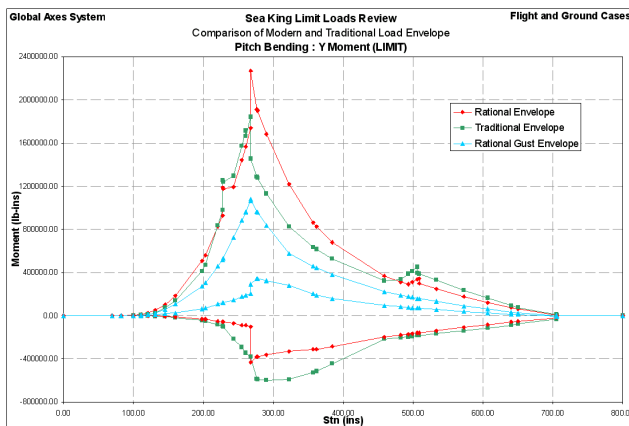


Figure 4 Comparison of Modern and Traditional Load Envelopes

Ageing Aircraft Review

On some airframe types the pragmatic choice will be to continue to operate beyond the arbitrary service life providing that the recent safety record and the cost of ownership trend is acceptable. This is justified by doing an ageing aircraft review and by constructing a rationale that delivers an “equivalent level of safety” to the historical basis on which the type has always operated. This can have a number of facets:

Those SSIs that are safety-critical and are covered by Safe Lives will either be subject to further testing to extend the lives or will be replaced as part of the life extension programme.

Other less critical parts of the airframe will continue with no substantiation basis, although in the case of Sea King, a flight envelope restriction is recommended as described above.

The decision to extend the life on this basis should not be considered irrevocable, indeed it must be kept under review. The safety trend of the type must continue to be acceptable.

The approach adopted by WHL in these cases is in-line with MASAAG policy (Reference 2):

- All structure is re-examined to confirm the list of SSIs.
- Where relevant, the design spectrum and actual usage are compared to ensure validity.
- The inspection regime is reviewed in the light of in-service findings to ensure timeliness of detection etc.
- The static clearance of the SSIs is reviewed especially in the light of service modifications and mass distribution changes or weight growth.
- Aircraft build standards are reviewed, on a tail-number by tail-number basis, to revalidate concessions, repairs and in-service modifications.
- A review of similar types under different usage conditions eg civil variants with high hours should be done.
- A tear-down of a lead airframe is done as described below.

Tear-down of Lead Aircraft

A key part of the ageing aircraft audit is the tear-down of one or more high hours airframes. This takes a lead airframe out of service and subjects it to an expensive, fastener-by-fastener destructive disassembly. The purpose of this is to look for new potentially critical failures, both fatigue and corrosion, that are not adequately covered by the existing inspection regime. The extreme case, albeit most unlikely, is where a critical failure mode is found that is underway in the tear-down item, and that cannot be inspected. If this were found, the fleet would be grounded and if replacement of the part were uneconomic the fleet would be retired.

Care is needed in selecting the airframe for the tear-down. For maximum benefit it needs to be picked on the basis of highest fatigue damage, most adverse build standard or worst environmental exposure. Inevitably, the airframe offered will be the one that the operator can most easily afford to lose – this is unlikely to meet the other requirements!

The key fact to consider about the tear-down is that it only gives information about the past – it is no guarantee for the future. The fatigue or corrosion damage must at least be microscopically detectable on the tear-down item to give useful information about the fleet. In other words a tear-down examination of an airframe at say 10000 hours gives some confidence that 12500 hours may be reached safely but does not clear the type to 20000 hours.

A tear-down of a Sea King airframe that has already accrued around 10000 flying hours is planned.

Life Extension: Economic Considerations

Cost of Ownership

As a rotorcraft type ages, maintenance and other operating costs will increase. The likelihood of fatigue failures increases with time. Recent work by WHL in conjunction with an export Lynx customer, has shown that the rotor passing vibration trend on each tail number shows a gradual increase with time. This is illustrated in Figure 5.

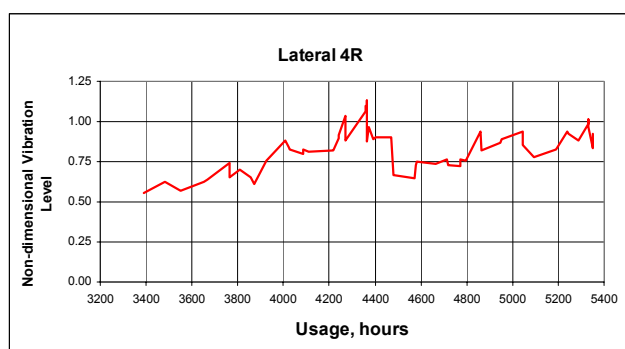


Figure 5 Trend in 4R Vibration as an Aircraft Ages

An increasing trend in vibration is common to all rotorcraft types and is probably due to gradual wear in the airframe joints and fasteners that either a) gradually moves the airframe natural frequencies down closer to the rotor forcing frequency or, b) reduces the airframe damping characteristics. This trend will accelerate the incidence of fatigue failures. Inspection and repair costs will clearly increase over time in order to manage the airworthiness implications of this trend. The importance of this trend will vary with each rotorcraft type depending on the placement of the structural frequencies relative to the forcing and the amount of damping of the modes.

Corrosion failures will also occur more frequently, with a non-linear trend over time. This is because corrosion will accelerate as corrosion protection measures, such as the wet assembly of joints (if used), anodic layers and the paint finish, break down

over time. The level of husbandry is clearly important in this instance since prevention is cheaper than cure and detecting failures early makes the remedial actions less expensive. Again, this trend will vary with each rotorcraft type depending on a number of factors such as:

- The selection of materials used in the design;
- The attention to corrosion considered by the manufacturer's design process (eg by minimising the risk of galvanic corrosion by avoiding dissimilar metals in contact), and;
- The quality of the anti-corrosion features built-in during manufacture (especially by conditioning the metallic surface and by ensuring the type and quality of the paint finish).

WHL, as a successful manufacturer of naval aircraft, prides itself on its expertise in the above field. It is interesting to note that the cost of ownership attributable to corrosion is much lower on WHL types than on those of other manufacturers.

Figure 6 below shows a generic non-dimensionalised cost of ownership trend. The estimated cost of ownership at entry into service achieved by design has been set to 100 units. Even the best qualified types will suffer some nuisance fatigue cracking in the first 1000 hours of service. For example, this might be an item of secondary structure, designed statically to crash cases, that suffers an unexpected vibration problem in service. These problems are normally rectified by redesign. Such problems account for the initial peak.

Thereafter, service experience might show that some inspection intervals were set conservatively, design improvements will be introduced, and the cost of ownership stabilises at a low level. Beyond about 6000 hours, however, the cost of ownership will start to rise for the reasons discussed above. The rate that this rises is the single most important economic consideration on the life extension decision.

The Figure shows two hypothetical cases – one where the cost of ownership rises sharply beyond 6000 hours and one where it rises gradually. In the case of the Sea King the latter is seen to be the case at the moment. Other manufacturer's products, if they lack the corrosion prevention measures employed by WHL, are more likely to follow the steeper curve.

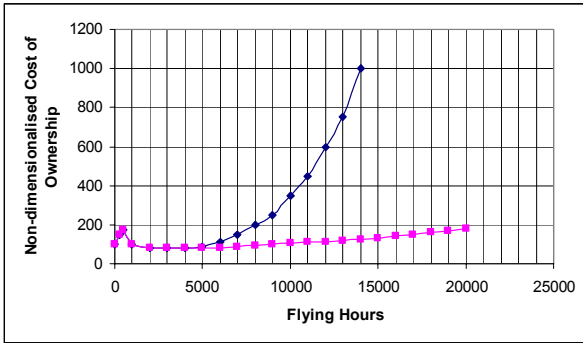


Figure 6 Generic Cost of Ownership Trends With Flying Hours

To illustrate the influence of cost of ownership on the re-airframing-versus-life-extension economic argument, the study shown in Figure 7 was done. The study only considered airframe costs and made no allowance for fuel, staff, avionics, depreciation etc. This was clearly but it did use realistic costs based on WHL experience. In this study, the total non-recurring cost of airframe redesign and requalification was estimated. It was assumed that redesigning the airframe will allow all of the known in-service problems to be solved and so the design resulting from this was assumed to have a low cost of ownership set at 1/5th of that of the current airframe. The cost of each new airframe was allowed for, as was the cost of stripping down and refitting all the rotors, transmissions and equipment from donor airframes. These costs were then compared with the total costs of inspecting and repairing airframes under a life extension programme. The non-recurring cost of the work required to give a life extension (airframe audits and re-testing) was also estimated and was 1/5th of the redesign NRC. The total cost of ownership was then computed over a further 10000 hours of airframe life with varying costs of ownership of the ageing airframes. It was found that, if the cost of ownership, attributable to the ageing airframe, goes up by 50%, then the re-airframing decision breaks even over about 30 airframes. If the cost of ownership attributable to the airframe does not increase as it ages, re-airframing never breaks even.

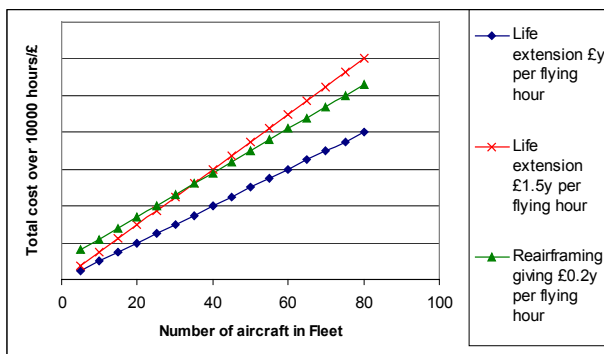


Figure 7 Re-airframing versus life extension break-even analysis

Factors in the Re-airframing Decision

Capability growth

The key factor in the decision to design a new airframe for Future Lynx was the fact that the UK MoD customer required significant capability growth. The main requirement was an increase in all up weight (AUW) from today's maximum of 5330 kg to 5790 kg at the in-service-date (ISD). The potential to grow to 6250 kg at the out-of-service-date (OSD) was also required. When the effect on airframe bending moments of this growth was computed, it equated to a growth in loads of 25% as shown in Figure 8. This was clearly beyond the capability of the existing design of airframe particularly aft of the rotor.

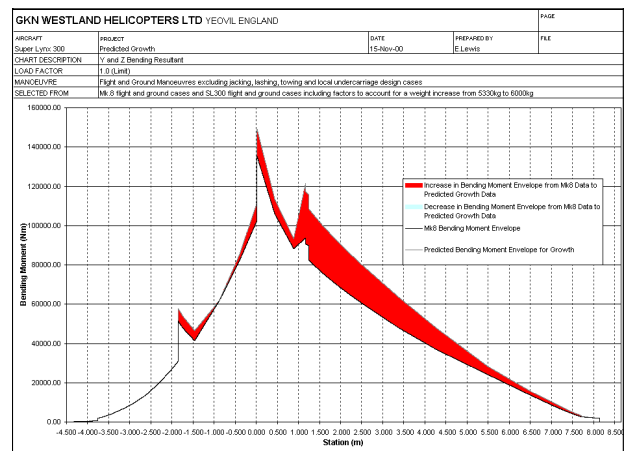


Figure 8 Growth in airframe design loads for Future Lynx

Cost of ownership

As described above, the cost of ownership of the Lynx airframe is likely to increase as the fleet ages for the reasons described above. A complete review of the in-service arisings and extensive discussions with operators identified a list of required improvements. The redesigned Future Lynx airframe will address the majority of known in-service fatigue and corrosion problems.

Crashworthiness requirements

The UK MoD's aspiration for Future Lynx is to have significantly enhanced crashworthiness and water impact survivability. The behaviour of existing Lynx was modelled using both non-linear (KRASH) and linear (NASTRAN) mathematical models. In addition, accident investigation findings were also considered. This work resulted in a number of design enhancement requirements, particularly in the strength of the bathtub and the incorporation of crashworthy seating. These changes will deliver 90th percentile crashworthiness for the new vehicle. The

crashworthiness features of Future Lynx are shown in Figure 9.

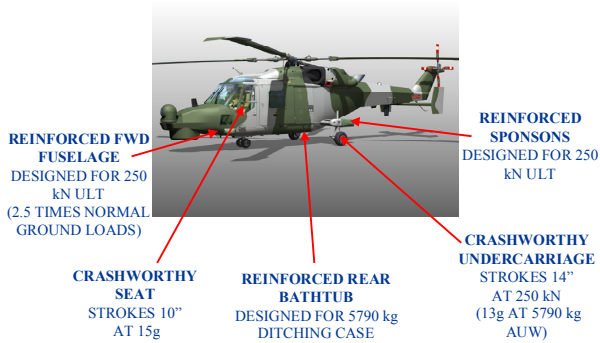


Figure 9 Crashworthiness Features of Future Lynx

Signature reduction

A design objective for any new military type will be to minimise the infrared and radar cross section signature. These factors have been considered in the design of the Future Lynx airframe. Amongst other things, right angles have been avoided where possible and composite hatches have been coated to make them opaque to radar.

Economics

The current Lynx airframe has evolved over the last 20 years. Most of the changes have been incremental and, like many older types, this now manifests itself in a complex, structurally inefficient design with a high parts count. One such area is shown in Figure 10.

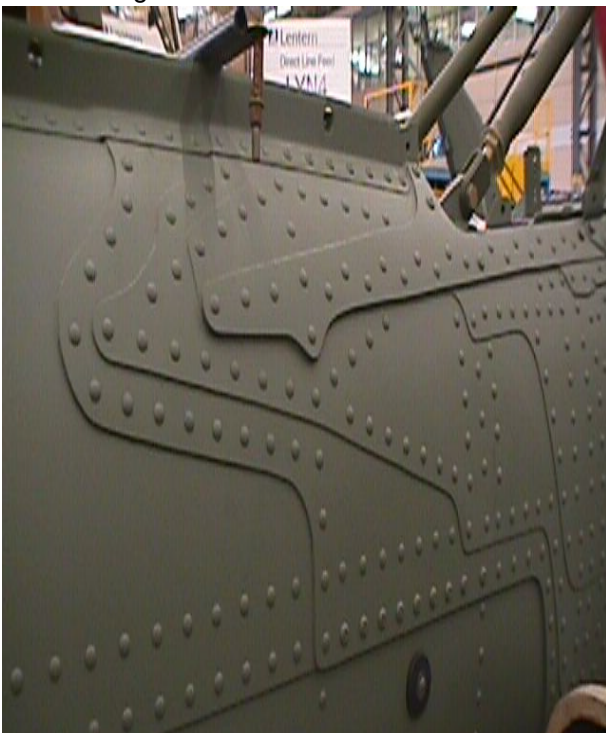


Figure 10 Example of incremental airframe growth

Future Lynx, because it covers around 100 airframes, represents a major opportunity to re-engineer the design and recover the non-recurring costs.

The design is at an advanced scheme stage and has already demonstrated that dramatic parts count reductions can be achieved. In some areas the new design has 1/10th the number of parts. For example on the tail pylon the parts count was 93 separate detail parts on existing aircraft that has been reduced to 11 in the new design. This has been achieved by the adoption of a machined-from-plate monolithic component construction philosophy. This is illustrated in Figure 11.

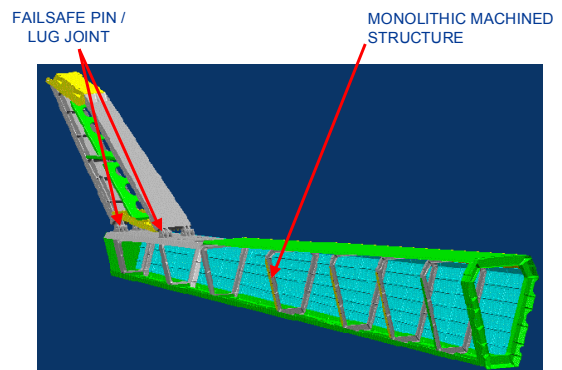


Figure 11 Future Lynx monolithic construction philosophy

These design changes have reduced the projected price of the airframe so much that the redesign and requalification cost breaks even over only 29 aircraft. This is solely on airframe build costs without taking account of the reduced cost of ownership.

Conclusions

This paper has reviewed the generic issues that must be considered by operators and design authorities as an airframe approaches its nominal service life. The decision to extend the life of the type has been contrasted with the decision to redesign and replace the airframe. Two current examples from the WHL portfolio, Sea King and Future Lynx have been examined.

In conclusion, the decision to pursue life extension is appropriate when one or more of the following criteria apply:

- Existing customers or the marketing organisation requires no capability growth for the type.
- The aircraft is no longer manufactured.
- The recent safety and cost of ownership trend of the type is satisfactory.
- An equivalent level of safety case can be made based for the continued operation of the type based on at least an ageing aircraft audit and a fleet leader tear-down plus perhaps operational restrictions.

The decision to re-airframe with a new design is appropriate when one or more of the following criteria apply:

- Existing customers or the marketing organisation requires capability enhancement beyond the capability of the existing design.
- The market niche is growing or still buoyant.
- The cost of ownership or safety trend of the type is unsatisfactory.
- A large order size allows non-recurring costs to be recovered.
- Modern manufacturing techniques allow dramatic parts count reductions and/or manufacturing cost savings.

References

1. DERA/MSS/MSTR2/TR000647, "Military Aircraft Structural Airworthiness Advisory Group – Annual Report FY99/00", September 2000.
2. MASAAG Paper P104, DERA/MSS/ASD(1)/11/6/4, "Recommendations for the future shape of the Ageing Aircraft Structural Audit", Issue A, 5th October 2000.