TITLE: Identification of Life Cycle Cost Reductions in Structures With Self-Diagnostic Devices

TITLE: Design for Low Cost Operation and Support [la Conception en vue d'une exploitation et d'un soutien a cout reduit]

Identification of Life Cycle Cost Reductions in Structures With Self-Diagnostic Devices

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1. Introduction

Life cycle cost (LCC) has become an essential parameter not just for accountants but also in engineering. It is not only the cost for product development or manufacturing which are the significant portions in aerospace applications but also those for maintenance, repair and maybe even disposal. Structures made of emerging materials such as carbon fibre reinforced plastics (CFRP) lead to new challenges for aircraft operators, one being the limited experience regarding maintenance and repair related LCC of these structures when compared to the experience gathered so far with metallic structures.
Another big challenge is the increasing number and age of aircraft and the desire of military aircraft operators to keep fighter flight control systems as flexible as possible. This situation makes prediction of real service load spectra more and more difficult when compared to the situation in the past. The solution to this problem is increased monitoring in the 'advanced' age of aircraft which leads definitely to increased LCC. A way to reduce this LCC portion is automation, where various solutions for structural health monitoring have been proposed [e.g. 9]. These solutions include the integration of sensing devices into the structure in a way that non-destructive testing can become an integral part of the structural material.
Within this paper an answer will be given to the question: *How far can automation and thus self-diagnostic systems help to reduce LCC?* This will be done by assembling maintenance data of different metallic and also composite components and deriving some cost estimating relationships (CER) before discussing potential LCC savings when integrating a self-diagnostic system. Most of the discussion will be made on the basis of the metallic components before predicting some possible LCC reductions with regard to CFRP components just entering their life cycle. Conclusions will finally be drawn with regard to future developments of structural health monitoring systems used for self-diagnosis of aircraft structures.

2. Ageing Aircraft and the Consequences

A look into the statistics of what is considered as ageing aircraft shows that the number of such aircraft is increasing annually. For civil aircraft this number has already exceeded 3.000 worldwide and an even larger number can be determined for the military sector. Following the various initiatives launched after the Aloha Airlines Boeing 737-200 accident in April 1988 and the regulations issued with regard to ageing aircraft, the amount of inspection required for ageing aircraft has been significantly increased. This additional inspection effort is however still within the range of LCC allowed by the operator. An operator's driven request is therefore related to automating the inspection effort and thus reducing inspection cost.
One answer to this request can be in using robots [10]. However solutions available today are still limited to be used on the aircraft's outer surface only and still requires manpower to interpret the figure monitored by the camera being built into the robot. This procedure is still quite time consuming and thus requires the aircraft to be taken out of service for quite a substantial time. Furthermore such an approach does not allow to inspect any hidden places in the structure (e.g. frames) without removing and reinstalling a significant number of parts.
A much more promising solution can be obtained from smart structures considerations. This 'smart' solution is based on integrating or adapting sensing elements into or onto a structural component using the sensors to either monitor a loads sequence and thus determine life consumed or to identify damage itself. A description of this 'smart' approach is given below.

3. Actual Trends in Structural Health Monitoring

Aircraft structures are based on one of the two design principles: *safe-life* or *damage tolerant design.* When *safe-life* is considered loads monitoring is the appropriate solution. From the load sequences monitored the actual fatigue life is calculated and thus allows to determine the incident when the component needs to be taken out of service. The advantage of this approach is that the component can virtually undergo any load sequence and is not dependent on a predefined load spectrum and the allowable flight hours as having been done so far. Loads monitoring can furthermore be used to predict residual life based on the actual load spectrum monitored.
Loads monitoring is also a basis for monitoring crack propagation in the context of a *damage tolerant* design approach. In that case crack propagation is calculated from the load sequence using fracture mechanics models. This however requires that the location of the crack is known, which is only possible when traditional non-destructive testing is included.
The biggest challenge however occurs when damage initiation is the feature to be monitored. Due to statistical effects this incident of damage initiation can easily vary in the range of the assumed life to damage initiation. It is one reason for the high inspection efforts required so far and the high penalties put upon allowable stresses or fatigue lives to meet required security levels. This burden may however be reduced through a structure adapted or integrated health monitoring system since such a system performs inspection automatically and furthermore allows to clearly determine the incident of crack initiation at individual locations, thus taking advantage of each components individual life without compromising the safety issues.
The principle of structure integrated health monitoring is briefly described in Fig. 1. It consists of a sensing device, possibly followed by an amplifier, a filter and a signal analyser before processing and thus interpreting the sensor signal data in a computer. Limiting the monitoring system to these elements allows to monitor loads (including impacts) or sig-

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nals being generated by the damage itself and being monitored by techniques such as acoustic emission. This however makes the monitoring system very much dependent on monitoring the occurrence of damaging events. Much more independence can be achieved if an actuation device is added to the structural component as well, because a signal can now be sent into the structure at any time, just as when performing ultrasonics, only that the monitoring system is now structure-inherent. A technique suitable for that purpose is acousto-ultrasonics.

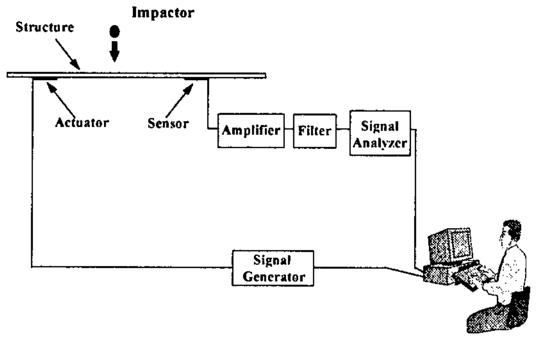

Fig. 1: The Acousto-Ultrasonics Principle

For the sensing device virtually any type can be used as long as it is able to monitor the respective frequencies being either generated by the load, damage or the actuation device. Two types have however been favoured during the past which is fibre optic and piezoelectric sensors respectively.

Fibre optic sensors are known to be advantageous due to their light weight, all passive configurations, low power utilisation, immunity to electromagnetic interference, high sensibility and bandwidth, compatibility with optical data transmission and processing, long lifetimes and low cost (as long as using silicon fibres). Disadvantages exist with the ability of repair as long as optical fibres have to be integrated into the material and placed according to major occuring stresses and strains for allowing to obtain reliable data. Fibre optic sensors have been proven to work for sensing strain as well as stress waves resulting from acoustic emission. Their integration into composite materials does not compromise the mechanical properties as long as the percentage of optical fibres is significantly low compared to the remaining fibre material.

Piezoelectric sensors are traditionally used for monitoring accelerations resulting from low or high frequency vibrations such as for monitoring vibrations in modal tests, Lamb waves or acoustic emission. Usually piezoceramic crystals are used which are relatively high weight and brittle. Recently piezoelectric ceramics have however been made available as small plates of different thickness, which can be cut to sensors of arbitrary geometry. These sensors may be bonded on the surface of a structure easily while integration into a structure is a greater challenge due to possible significant differences in mechanical properties between host and piezoelectric material. Recent research work is also looking at developing piezoelectric fibres to be integrated into composite materials. In the context of the acousto-ultrasonic system mentioned above, piezoelectric devices have the advantage of being used as actuation devices as well. This is why a monitoring system based on piezoelectric devices will be considered here.

Piezoelectric elements can be individually attached to or integrated into a structure and the different elements need to be connected by wires. However this is not the ideal solution for a kit which has led to development of what has been denoted as the smart layer [11, 12]. The principle of such a layer is shown in figure 2. It consists of two Kaptone foils, where tiny piezoelectric sensors as well as the required electric wiring is integrated in between, similar to the way this is done for electronic components. These layers can be either integrated into a composite structure or patched on the outside of any kind of structure (e.g. metallic, polymer, composite, etc.). Beside damage and cure monitoring they are also an interesting solution regarding monitoring of repairs. Smart patches can be configured with that technology which can be used for autonomously monitoring damage critical components. A software for generating the input and analysing the output signal is also provided. Sensor signals might be pre-processed on a built-in chip before being remotely transmitted to a full signal processing station.

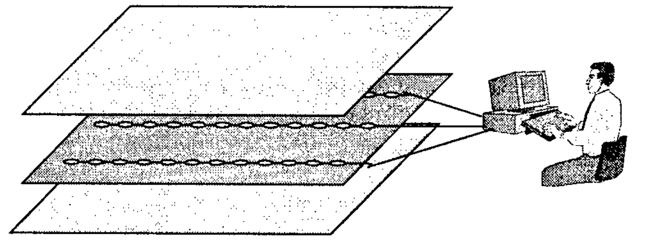

Fig. 2: Smart layer concept

Within the following chapters such a smart layer solution will be considered with respect to potential LCC savings on aircraft components. Since such solutions are especially attractive in the ageing aircraft environment, different metallic components will be considered first followed by an estimate on what possible LCC savings could be achieved one day with CFRP components.

4. The Life Cycle Cost Process

4.1 Background

Life cycle cost analysis is defined as "a general method of economic evaluation which takes into account all relevant costs of a building design, system, component, material or practice over a given period of time adjusting for differences in the timing of those costs" [4].

This includes in general costs for [5]:

1. Research and development (R & D) (C_{R+D})
   Initial planning, market-analysis, feasibility studies, software, documentation, project management etc.
2. Production and Construction ($C_{Manuf.}$)
   Industrial engineering, manufacturing labour, material, tooling and machines, process development, quality control and initial logistics support requirements (e.g. manufacture of spare parts).
3. Operation and support (O & S) (C_{O+S})
   Maintenance, storage for spares, fuel costs, test and support equipment, transportation and handling, technical data, system modifications etc.
4. Retirement and disposal ($C_{disposal}$)
   Disposal of non-repairable items throughout the life cycle, system/product retirement, disassembly and material recycling .

LCC is thus determined as the following summation of these cost parameters:

$$LCC = C_{R+D} + C_{Manuf.} + C_{O+S} + C_{Disposal}$$

The target of life cycle cost analysis is the development of a cost profile that models the cost distribution over the complete life cycle of a product as detailed as possible. According to [5] the method for building a life cycle cost model can be subdivided into the following steps:

1. Identification of all activities contributing to costs within the product's life cycle.
2. Assignment of activities identified under 1. in a cost breakdown structure (CBS) where a rough overall example of such a structure is given in fig. 3. Possible variants regarding different product variants, manufacturing processes and maintenance concepts should be included as well.
3. Establishing cost estimation relationships (CER), either self-developed or using parametric cost estimation models and tools (e.g. [8]).
4. Decision upon the reference date to be considered, which is either the value of LCC today or at a future date (e.g. the day of disposal), where the conversion follows an equation

$$x(t1) = (1 + \frac{y}{100})^{(t2-t1)} \cdot x(t2)$$

   with *x, y, t1* and *t2* corresponding to cost, interest rate (% p.a.) and two different points of time respectively.
5. Introduction of learning curves to account for technological improvements over time.
6. Summarisation of the different cost profiles within the CBS.

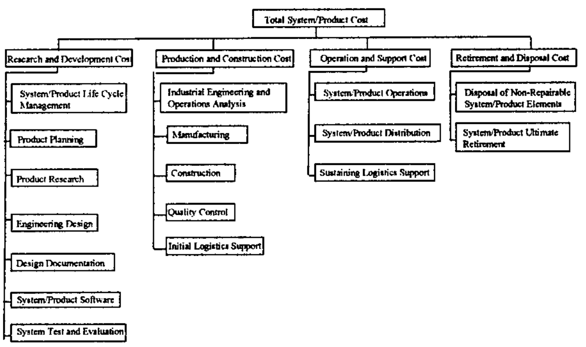

Figure 3: Cost Breakdown Structure [5]

The problem to be tackled with structural health monitoring is purely related to inspection, which is a sub-division within the O&S cost element. Assuming that the structural health monitoring device such as a smart layer is a device purchased through a supplier and thus neither generating non-recurring development cost nor interfering with the standard structural design, LCC reductions can thus be considered in an isolated approach as a reduction in inspection cost only. To however briefly describe the whole frame of the LCC model, a short overview of the O&S element is given below.

4.2 Operation and Support Model

Within the military aircraft environment O&S cost can be determined according to a methodology described in [3] thus containing information about

- maintenance planning
- repair analysis
- support and test equipment
- supply support
- manpower, personnel and training, etc.

There are also software tools available today for determining O&S cost (e.g. [6]). However such tools can easily require around 100 input parameters such as being related to:

- Parts, which includes unit cost, production volume, repair cost, mean time between failures (MTBF), etc.;
- Equipment, considering the system (e.g. aircraft) into which the considered part is built in;
- Environment, including the wide range from annual inflation and discount rate, annual billet cost for maintenance technician, number of repair depots, etc..

An overview of the calculation procedure is shown in fig. 4. A detailed look at this O&S split does however not give much information with regard to inspection cost. Due to this the respective data had to be retrieved directly from interviewing skilled maintenance personnel and converted into a model which is described in more detail below.

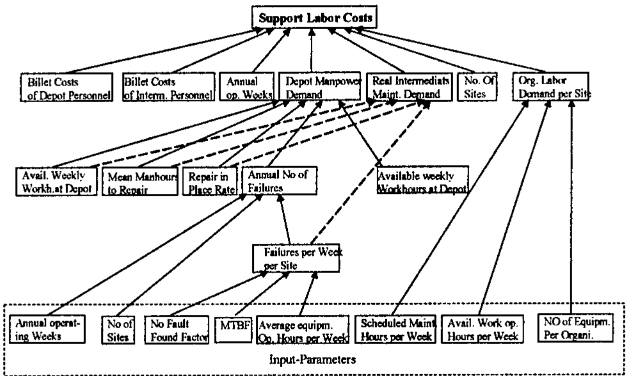

Figure 4: Calculation principle for the maintenance cost (simplified)

5. Case Studies

5.1 General

To determine the possible LCC potentials of implementing a structural health monitoring system (SHMS) into or onto an aircraft structure, a pragmatic procedure was established being based on a limited amount of maintenance data. This data was obtained as average numbers observed over a ten years period from experienced maintenance personnel. Two types of aircraft components were considered:

- Metallic components, where a large experience was gathered and thus data for different components could be obtained;
- CFRP components, where only very limited experience and thus data could be retrieved.

The approach was therefore outlined such that a CER model with respect to inspection effort could be determined for the metallic components and then converted to conditions for CFRP structures using the limited data for CFRP mentioned above.

5.2 Metallic Components

In the first step an analysis of the inspection effort distribution of metallic components of the TORNADO airframe was performed.

The distribution of the aircraft structure visual inspection effort is shown in fig. 5. It shows that the majority of this inspection is related to the aircraft fuselage and only very little to surface check for corrosion.

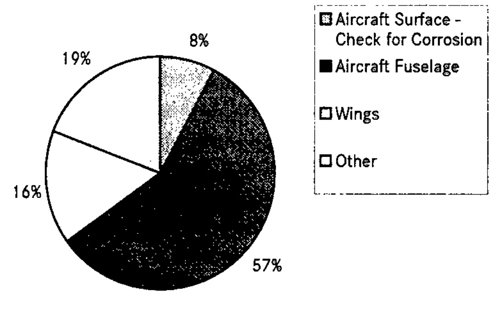

Fig. 5: Distribution of airframe visual inspection effort

The biggest part of the airframe inspection effort is due to visual inspection (61%), followed by unplanned NDT (31%) and planned NDT inspections (8%), see figure 6. The unplanned NDT inspections are in general due to the examination of assumed failures and repaired parts.

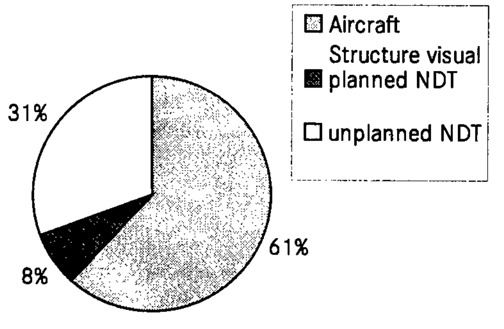

Fig. 6: Distribution of airframe inspection effort

With regard to metallic materials, six different components of the TORNADO fighter aircraft were considered which included:

- Two different types of fittings (fig. 7),
- Two different types of covers (fig. 8),
- A tail section skin (fig. 9), and
- The taileron (fig. 10).

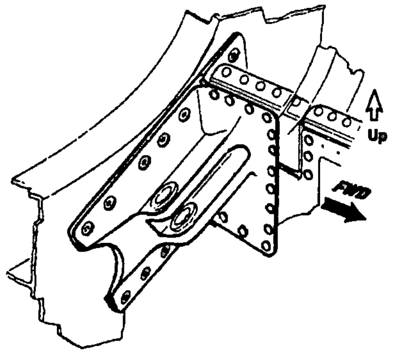

Fig. 7: Main Landing Gear Fitting

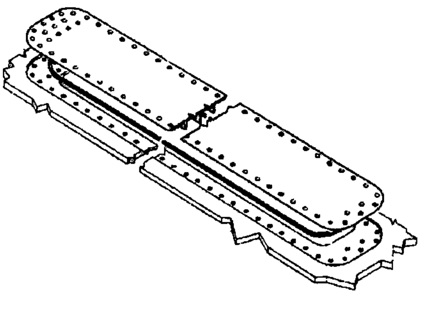

Fig. 8: Cover

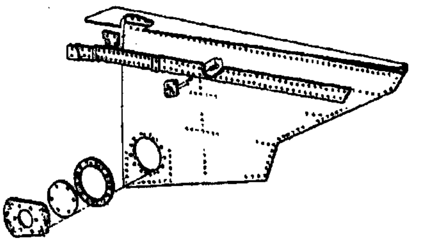

Fig. 9: Tail Section Skin

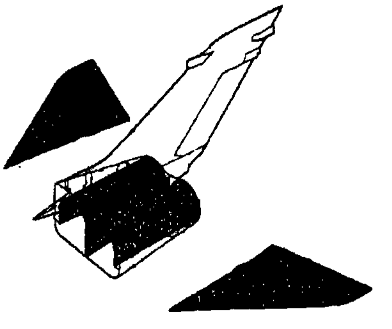

Fig. 10: Taileron

Inspection data being available for these components were:

- average inspection time,
- inspection frequency,
- MTBF,
- damage type, and
- average repair effort

Inspections being performed before and after flight as well as those being defined as minor, periodic and during depot were considered.

In many cases just maintenance cost is given, which also includes repair. Analysing the data of the six components considered here led to the conclusion, that a 50 to 50% split of the depot maintenance cost between inspection and repair for the 6 sample parts respectively is a good approach (fig. 11).

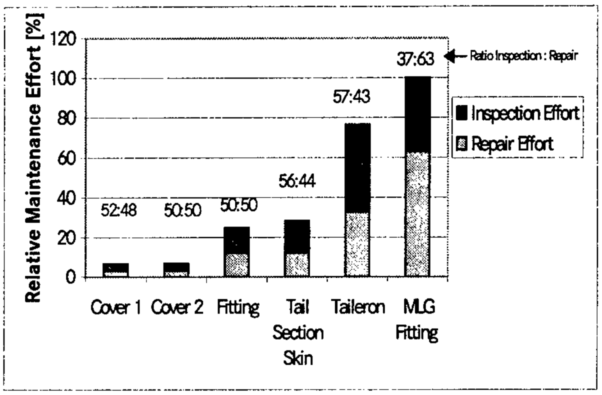

Fig. 11: Distribution of depot maintenance effort for different metal structure parts

To determine an inspection related CER model for the metallic components a more detailed analysis of the inspection effort was done which resulted in the following parameters x_i driving the CER:

- surface area [m^2] (x_1),
- number of rivets (x_3), screws (x_2) and drilled holes (x_4),
- severity of loads (x_6),
- inaccessibility of the component (x_5),
- inspection criteria (corrosion (x_7), ruptures (x_8) or loosening (x_9))

With the exception of surface area and number of rivets, screws and holes, which are explained by themselves, the parameters were defined as follows:

- Inaccessibility
  - Very easy access to part – no assembly necessary: $x_5=1$
  - At least one assembly step necessary to access part: $x_5=2$
  - Difficult access to part: More than one assembly step necessary: $x_5=3$
- Load
  Low: $x_6=1$
  Medium: $x_6=2$
  High: $x_6=3$
- Inspection criteria
  Here flags have been set with flag equal to 1 meaning that the criterion is valid and 0 if being not valid.

To clearly identify the total inspection effort this was split into the following shares being related to:

- Dismantling and assembly I_1
- Visual inspection against corrosion I_2
- Visual inspection against loosening I_{2b}
- NDT inspection against ruptures/corrosion I_3

Based on the above described parameters and having all inspection efforts referenced to the inspection effort of the fitting with the highest inspection cost (MLG fitting), the following equations were derived:

- Dismantling and assembly
  This is mainly a function of part dimensions (surface) and inaccessibility. The following CER was found for the prediction of the dismantling and assembly time (see fig. 12):

$$I_1 = (12{,}66 + 71 \cdot x_1) \cdot (x_5 - 1)$$

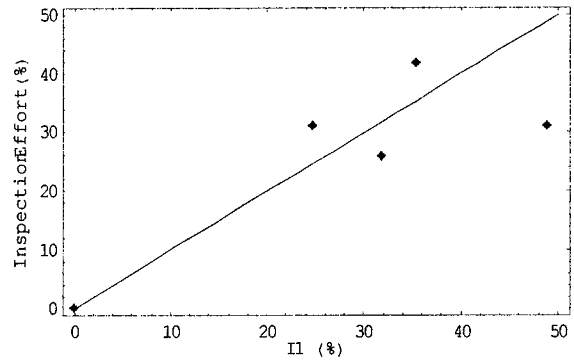

Fig. 12: CER for Assembly Effort

- Visual inspection
  Checking a part for corrosion or loosening of screws have been the major drivers here. The result shown in fig. 13 was determined by the following equations for corrosion

$$I_{2a} = 2{,}6 \cdot x_1 \cdot x_7$$

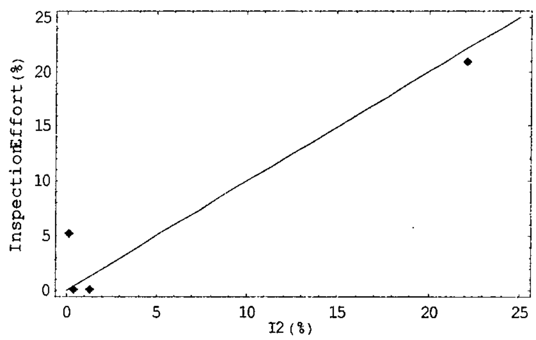

Fig. 13: CER for Visual Inspection Effort

and loosening of screws

$$I_{2b} = 0{,}77 \cdot x_9 \cdot x_2 \cdot x_6$$

respectively.

- NDT inspection
  The NDT inspection effort was found to be nearly constant for all parts that are inspected against ruptures:

$$I_3 = 22 \cdot x_8$$

The total inspection effort per part is summarised to be:

$$I_{total} = \sum_{i=1}^{3} I_i$$

Since the CERs are so far related to depot inspection only an integration has to be performed to obtain the inspection related LCC. This has been done using the table shown below and including the frequency of the different inspection types.

Inspection Type	Taileron	Tail Sec. Skin	Fitting 1	Fitting 2	Cover 1	Cover 2
Depot	•	•	•	•	•	•
Periodic	•	•		•		
Minor		•				
Before/After Fl.	•				•	•

Table 1: Inspection Frequency Distribution of the Sample Parts

A comparison of inspection related LCC between the prediction using the CER-model and the real LCC efforts is given in fig 14. With the exception of cover 1 and fitting 1 where a difference of up to 80% is observed, the predictions are fairly acceptable. The larger deviations are aminly due to inaccuracy of the database.

An extension of the database might certainly help to furthermore improve the model.

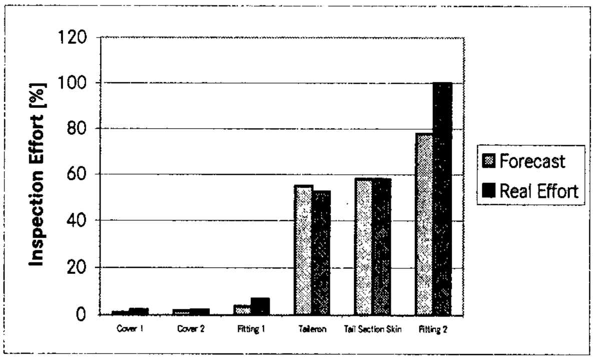

Fig. 14: Validation of the CER Model

5.3 CFRP Components

As mentioned earlier the amount of inspection and/or maintenance data being related to CFRP components was very much limited to either some demonstrator components (e.g. main landing gear doors of TORNADO) or the little experience gathered so far with the seven Eurofighter Typhoon test aircraft flying around with the different Eurofighter partners. Although these components have been designed to be maintenance free, inspection is actually still performed with regard to the relative novelty of CFRP in high performance aircraft structures as well as the need to verify that the requirement of non-required maintenance has been met. The inspection effort which is actually performed on these components is relatively high and has therefore to be considered at the very beginning of any learning curve. To determine how this inspection effort may decrease in the future, a look to learning curves for safe-life metallic components of the past may be useful. Such a curve is shown for a Boeing 707 airframe in fig. 15 .

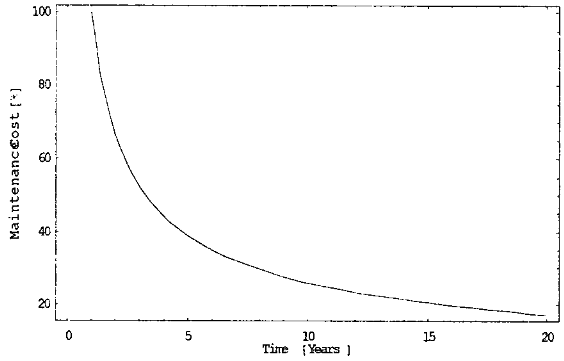

Fig. 15: Maintenance Cost Model for Boeing 707

What can be concluded from that figure is, that maintenance and thus NDT effort has not vanished after 20 years although the components considered have been safe life. It is thus that a similar trend can be expected for the CFRP components used today which have also been designed safe life and long term maintenance free.

Another question with CFRP is to what extent the inspection effort increases if the component design is converted from safe-life to damage-tolerant and what weight savings can be expected under these conditions. So far the available data is much to rudimentary but in the longer term analysing such an aspect might be worthwhile doing for giving an answer to this question.

5.4 Structural Health Monitoring System

Due to the novelty of SHMS, the estimation of resulting LCC reductions has still to be very much based on assumptions and is therefore somehow speculative. However it is only with these estimations that guidance can be received regarding the focus of future development. With regard to the SHMS considered here the smart layer solution as described above was selected. Regarding LCC, the following cost aspects were considered:

- Production cost, which consisted of the purchasing cost as obtained from the supplier and
- Maintenance cost

R&D cost was considered to be included in the production cost and retirement and disposal cost was considered to be negligible.

SHMS are actually still in a R&D stage. The solutions being therefore available today are still mainly prototypes and thus at the very initial stage of a learning curve. Considering the smart layer system, this can be split into three major elements being:

- The smart layer itself consisting of the Kaptone foils with integrated piezoelectric elements and the respective wiring.
- A chip with integrated antenna being either implemented onto the smart layer or close to it, allowing to perform sensor signal pre-processing and sending the pre-processed signals to a central data processing unit.
- The software in general, allowing to process the sensor signals and to determine damage with respect to location and severity.

As done for the different components before, the cost figures for the SHMS have been referenced to the inspection related LCC as well.

For the smart layers of 30 x 60 cm in size and being equipped with 12 piezoelectric elements, the cost per layer is around 13% today. A target price of 0,3% can however be expected, once a serial production can be started and the manufacturing process is much more automated .

For the electronic unit consisting of a standard ASIC chip and an antenna the target price for a serial production should not exceed 0,08%.

Software cost is difficult to estimate but some comparison can be possibly made with the avionics sector. Assuming a ratio software to hardware cost of 50:50 for the smart layer system leads to software cost in the area of 0,6% for the serial part.

Attaching the smart layer to the respective component and testing of functionality should be done within 30 minutes each when being in the saturation phase of the learning curve. An equivalent absolute value in the range of 0,1% to 0,3% has therefore to be added which however depends on local labour rates. For the manufacturing labour for the SHMS 0,2% are considered.

With respect to O&S cost of a SHMS about 50% of the manufacturing cost can be applied as maintenance labour effort.

Adding all these different cost elements together allows to determine in what order of magnitude LCC of such a structural health system can be expected. Figure 16 compares the cost structure of the prototype and the serial part.

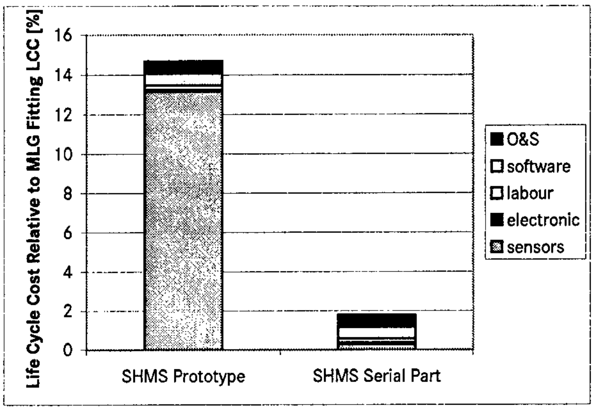

Fig. 16: Cost Structure of the SHMS Prototype and the Serial Part

When comparing the results obtained in fig. 16 with a standard learning curve for electronic components it can be seen, that the estimate quite well meets standard experience and the assumptions have not been unrealistic (fig. 17).

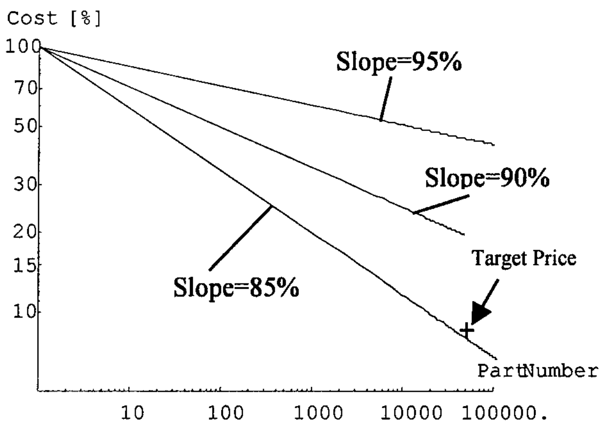

Fig. 17: Learning curves for Manufacturing of Electronic Elements

5.5 Trading the Inspection Cost

Compared to the CERs having been determined and described in chapters 5.1 and 5.2 respectively, it is now possible to estimate how far a SHMS can be beneficial for metallic and composite components of either shape, loading or degree of accessibility. Before however trading these numbers it should be clear that although a SHMS aims at reducing inspection cost, it is quite unlikely that it is able to reduce inspection cost to zero. A better question to ask is therefore: ***What is the portion of the structural health monitoring LCC when compared to the actual LCC portion for inspection of the component considered?*** This ratio is therefore shown for metallic components under consideration of the SHMS prototype and serial part costs and for a CFRP component in the figures below (fig. 18, 19 and 20). As metallic components the above described TORNADO components and as CFRP component the TORNADO main landing gear door were selected.

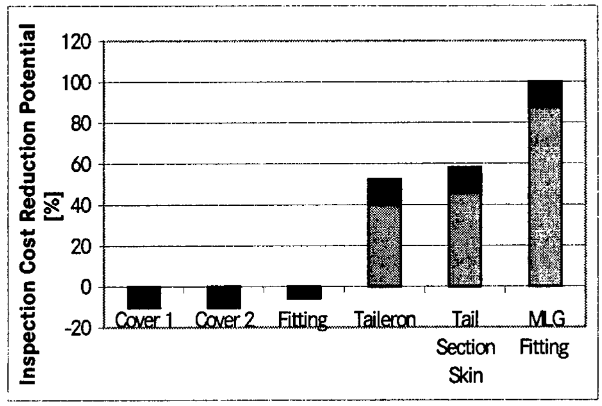

Fig. 18: Potential LCC Savings through SHMS for Metallic Components (Assumption: SHMS Prototype Cost)

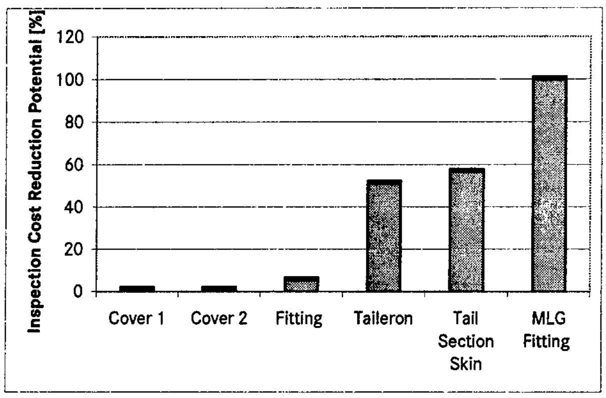

Fig. 19: Potential LCC Savings through SHMS for Metallic Components (Assumption: SHMS Serial Cost)

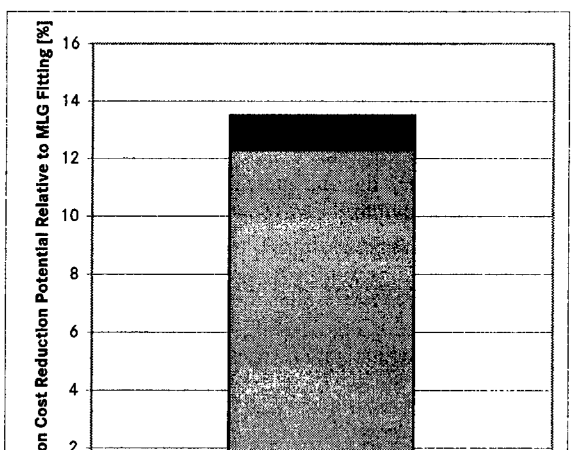

Fig. 20: Potential LCC Savings through SHMS for CFRP (Assumption: SHMS Serial Cost)

What can be seen for the metallic parts is, that there are types of components such as the covers, where a SHMS does not make much sense under the assumption of the SHMS prototype cost while on the other hand components being highly loaded and difficult to access can highly benefit from implementing a SHMS. Under the assumption of the SHMS serial part cost even for the cover parts a cost benefit can be achieved.

Although only one CFRP component could be considered here, a similar trend can be considered to the one determined for the metallic components. However due to the relative novelty of CFRP when compared to metallic structures, the cost savings potential for CFRP components with a SHMS is actually still high. A proof is the cost savings shown in fig. 20 for the CFRP main landing gear door which is an easily accessible component with no severe load conditions. This trend will therefore change when CFRP will become as standard as metals are today.

6 Conclusions

This little study has shown, that with a small number of representative components a trend can already be shown on how far SHMS can help to reduce inspection related LCC. What needs to be done is to identify the appropriate CERs where the significant parameters can be limited to a manageable number. Based on these parameters it is possible to perform trade studies which allow to identify which components of an aircraft are worth to be considered for adapting an SHMS and which are not.

Definitely an increase in the number of components included in the CERs can help to improve the costing model. This is certainly what will be done in a next step. It is however already now possible to conclude that there is a significant number of components on aircraft where a SHMS can lead to remarkable LCC reductions as soon as SHMS becomes commercially available. Technology for SHMS is quite advanced already and it is just a question of time, when this commercialisation will start.

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