Structure Integrated Sensing and Related Signal Processing For Condition-Based Maintenance

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Introduction

Progress in monitoring technology has allowed to extend the operational life of existing engineering structures reducing operational cost without compromising security. This has led to an increasing number of ageing aircraft and civil engineering infrastructure, where a large discussion is still ongoing for now more than a decade. One conclusion from that discussion with regard to aircraft is, that they can still be operated beyond their initial operational life, if the initial operational life can be sufficiently well described and operational conditions as well as occurring damage is frequently monitored during the succeeding extended operational life.

Another aspect being quite specific for military fighter aircraft is that they are often partially used different compared to their initial design. The positive case includes the situation that fighters have been luckily used in less serious conditions than they have been designed for, which has resulted in less accumulated damage than initially considered. This has led the aircraft operators to take advantage of the still remaining portion of damage to be accumulated by extending the duration of operating the aircraft and thus reducing operational cost.

Aircraft however do not consist of a structure alone. Other and nowadays sometimes even more recognised elements include propulsion, avionics and specifically with fighter aircraft flight control and weapon systems. These elements partially undergo remarkable technology innovation cycles and it is the specific desire of the aircraft operators that their aircraft benefit from this innovation, even when the structure is old and still allows for a significant number of years to go. This combination of 'old' structure and innovative flight and mission technology easily leads to a change in operational conditions, which the structure was not initially designed for. Modifying the structure according to these conditions is usually impossible so the remaining solution is only to continuously monitor the operational loads followed by an assessment of accumulated damage.

Smart materials and structures which mainly includes the integration of sensing and possibly even actuation devices into or onto the structural material combined with advanced signal processing and possibly even control, can provide an interesting platform for such continuous monitoring on a low cost automated basis, thus allowing to perform condition-based maintenance.

This paper will describe the actual maintenance issues from an aircraft perspective and options provided from smart materials and structures with regard to cost-effective condition-based maintenance.

Operational Loads Monitoring

When the Comet commercial aircraft was designed as one of the possibly most innovative aircraft ever designed, including features such as a pressurised fuselage, jet engines and damage-tolerant design based on latest findings in fracture mechanics technology of that time, the aircraft was only able to survive 1290 flight cycles before it crashed in the Mediterranean Sea in 1954. It was specifically the quick application of fracture mechanics which led to erroneous assumptions and to revisiting the application of fracture mechanics and fatigue in aerospace. The quickly resulting consequences included the introduction of major airframe fatigue tests (MAFT) and onboard loads or initially even just exceedance monitoring systems. The main purpose of MAFT is to determine the fatigue critical locations beforehand and to issue the respective modifications with respect to design, manufacturing, maintenance and repair. The introductions of onboard loads monitoring, which has been so far only applied for mainly safe-life designed fighter aircraft, was considered to verify if the initially considered load sequences were not exceeded.

In a safe-life design environment damage is defined to be something which cannot be directly measured as a quantity by standard non-destructive testing techniques. Damage D for each structural component is therefore estimated according to Palmgren-Miner's rule as the accumulation of damage D_i of each individual load cycle, where D_i is the inverse of the number of cycles N_i the component is able to endure.

$$D = \sum_i D_i = \sum_i \frac{1}{N_i}$$
$$N_i = f(S_i)$$
$$S_i = f(Loads)$$

Since the number of cycles to endurance N_i is a function of stress S and stress a function of loads, a stringent relationship between loads and damage is established. However a further number of material inhomogeneities and assumptions in linearisation of damage accumulation interfere, which lead to what is known as scatter and becomes specifically difficult to monitor. In design this behaviour is covered through a scatter factor, which basically is a shift of the fatigue-life curve into a region of low probability of fracture.

The approach has been used over decades and has been continuously refined. The early loads monitoring systems were simply based on vertical acceleration n_z of the aircraft, multiplied by the aircraft's mass to obtain a force. Current systems are based on monitoring strain- and thus load-sequences at fatigue critical locations by either using strain gages or flight-parametric systems. While the former system simply requires a strain-gage to be bonded to the fatigue critical location, the latter is based on recording flight parameters such as speed, altitude, acceleration, flaps position, fuel content, etc., which are then fed into a load transfer function having been determined earlier from the loads model. The logic of such a procedure is shown schematically in Fig. 1.

With the availability of digital loads models it is nowadays possible to extend the above logic be feeding the required sensor information into the loads model and to be able to estimate consumed life or inversely accumulated damage at virtually any fatigue critical location on the aircraft. This may become specifically important with a change in flight envelopes, weights or any other modification required.

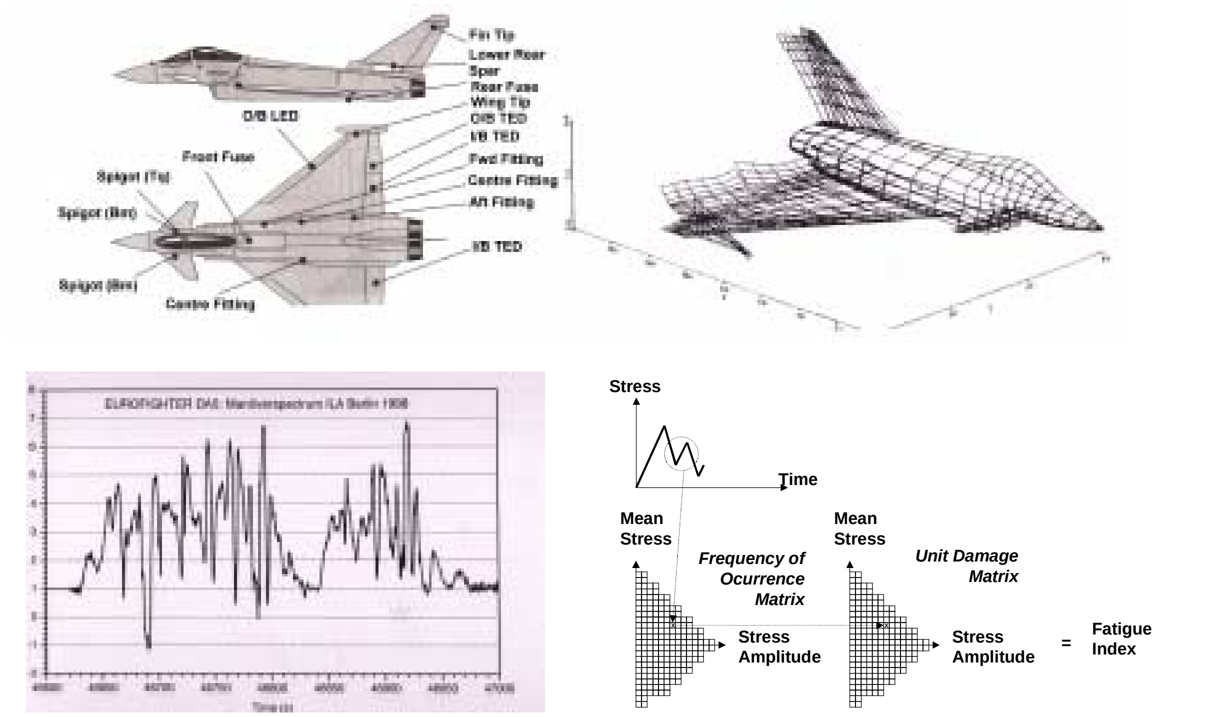

Fig. 1: Eurofighter Typhoon Loads Monitoring Logic

All loads information gathered on the aircraft is downloaded on ground and processed on a squadron level (Fig. 2).

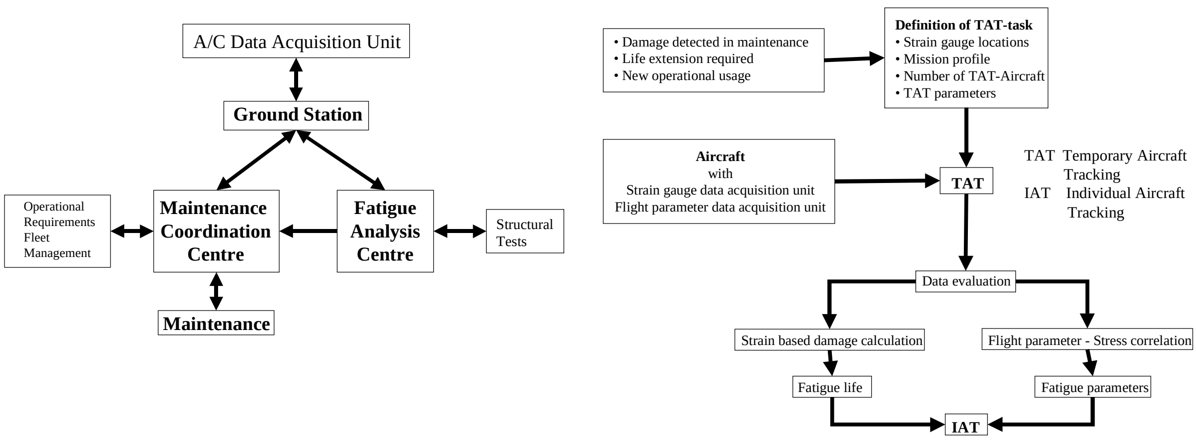

Fig. 2 Loads monitoring based aircraft tracking procedure

This allows a squadron leader to decide which aircraft to be used in which mission and to balance usage of aircraft such that damage of the different aircraft is relatively equal.

Operational loads monitoring has not been very popular with civil aircraft so far but with military aircraft it definitely is. Caron and Richard [1] were able to show, that the operational life of the F-18 of the Canadian Air Force could be extended by 12 years due to operational loads monitoring, thus leading to a savings of 400 Million Can$. Performing this type of monitoring led to:

- Better control the fatigue life consumption of each individual aircraft,

- Properly estimate the aircraft retirement time,
- Efficient management of the aircraft maintenance program,
- Identify that the aircraft in-service usage was more severe than anticipated,
- Pilots to better understand the impact of different flight techniques.

All what has been described so far here has been related to metallic structures. Operational loads monitoring has however not to be limited to this class of materials only. Composites is nowadays widely used in aerospace, where damage is however less critical with fatigue than with static and impact loads. The type of load has therefore to be monitored, where solutions have been proposed on a more generic level so far [2]. The logic here is to define an impact threshold (e.g. an energy) above which a damage (e.g. delamination) has to be assumed.

Ageing Aircraft – The Need for Damage Monitoring

Remarkable effort has been put on improving the applicability of fail-safe design since the Comet accident in 1954. Major achievements have been the above-mentioned operational loads monitoring, better understanding of stress concentrations and intensities around notches and cracks as well as improved detectability of cracks using non-destructive testing (NDT) methods. This allowed the fatigue life to be extended from the 1290 flight cycles of the Comet to the more than 80.000 flight cycles which the Aloha Airlines Boeing 737-200 was able to achieve before it suffered a serious accident in 1988 caused through what has been specified as multi-site damage (MSD) later. It has been specifically this accident which has put a major focus on direct damage monitoring with regard to ageing aircraft. While up to the Aloha Airlines accident cracks detected by NDT were only considered to occur singular at very few locations, it now became apparent that occurrence of adjacent cracking becomes much more likely at various fatigue critical locations of an ageing aircraft. Such a proximity and thus much higher density of cracks accelerates crack propagation significantly. A typical element for such a configuration is a rivet line, which has also been the source for the Aloha Airlines accident. As shown in Fig. 3 schematically it makes a significant difference if a single crack

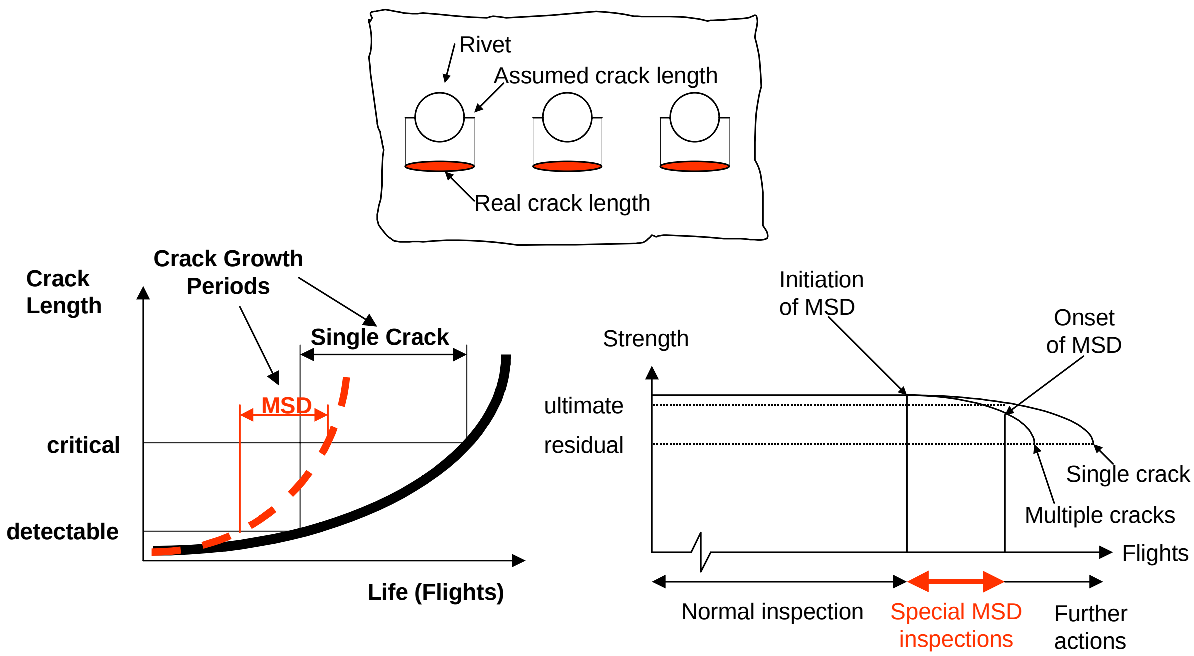

Fig. 3: Multi-Site Damage schematic and consequences

of say 1 mm is detected just on one side or on both sides of the rivet. In the former case it can still be considered as a 1 mm crack while in the latter case it becomes a *2 x 1 mm + rivet diameter* long crack which can easily be something around 10 mm in crack length. If such long cracks even occur at different rivets, crack propagation of the structure becomes worse and may result in a very reduced crack propagation life.

MSD has specifically initiated a number of activities with regard to ageing aircraft which includes:

- Better understanding of locations being prone to MSD,
- The influence of MSD on crack propagation behaviour, and
- Special MSD inspection schemes.

Better understanding of locations prone to MSD has been achieved by gathering as much information as possible on in-service inspections and specifically tear-down analysis of either the completed MAFT structure or early built aircraft having achieved their design life goals. Damage critical locations are inspected with regard to occurring cracks and the respective loads and the information is fed into a database which allows to perform statistics on crack distributions and thus likelihood of crack occurrence. Such analyses and specifically databases then allow to determine locations which have to be specifically monitored with regard to MSD. An example for the result of such an analysis is shown in Fig. 4 for the early Airbus A300 series.

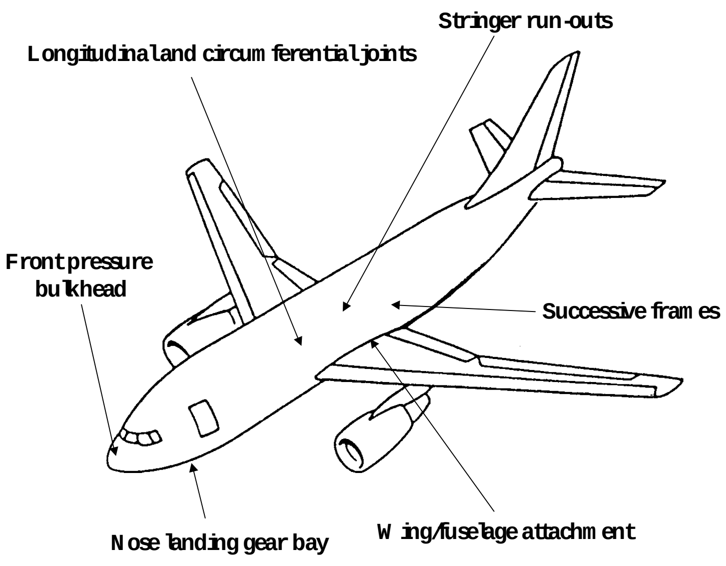

Fig 4: MSD susceptible structures identified for Airbus A300

To better understand and possibly formulate and communicate the aircraft structural integrity process, the United States Air Force defined the Aircraft Structural Integrity Program (ASIP) in the early 70ies, which has been adopted and possibly even adapted by regulation agencies in many countries. It is organised into five tasks which include (1) Design Information, (2) Design Analyses & Development Tests, (3) Component and Full Scale Testing, and two tasks (4 & 5) being related to Force Management Data Package. ASIP offers a holistic management plan covering all aspects of the integrity process. An ASIP conference is held every year where a large amount of data and information is shared and activities are generated. One of such activities is the development of the computer programme PRobability Of Fracture (PROF), which is based on deterministic damage tolerance analysis data and an initiating distribution of crack sizes in the population of details. The programme uses stress and crack growth data that are known to be available for all critical locations of structurally significant details which have been compiled and generated through ASIP. PROF then calculates the probability of failure as a function of flight hours from the joint distribution of crack sizes, maximum stress per flight, and fracture toughness. A schematic of the inputs and outputs of that process in shown in Fig. 5.

These instruments and procedures basically allow to determine the damage critical locations on an aircraft, which need to be monitored after a certain period of usage.

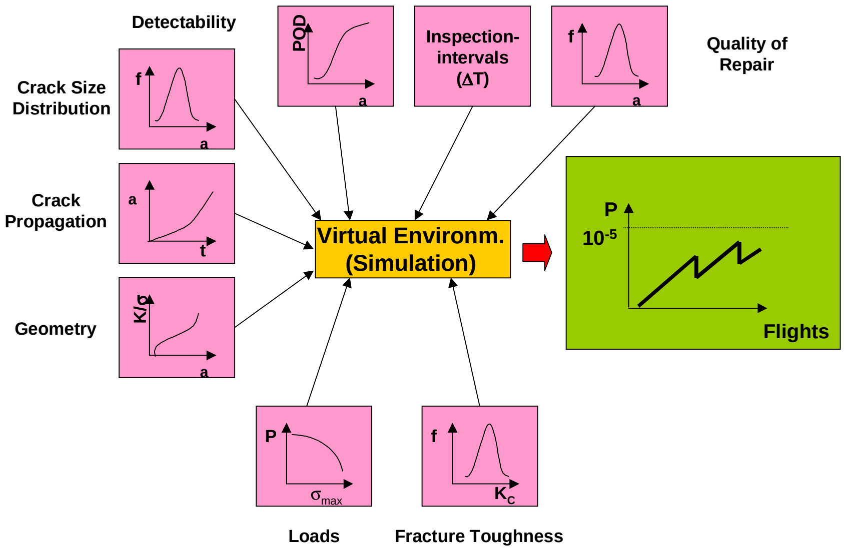

Fig. 5: PRobability Of Fracture (PROF) schematic

Structure Integrated Damage Monitoring Techniques

As soon as damage is predicted to occur on a component, the component needs to be monitored. This process of monitoring may become costly because the location of damage is at a relatively 'remote' place in the aircraft which needs a lot of dismantling before the location can be monitored. Although a damage may be analytically predicted, its true incident of occurrence can still take a significant amount of time. This amount of time can however not be taken advantage of in a safe-life design, except the damage critical location is regularly monitored. Automated monitoring procedures can therefore allow for more damage-tolerance in safe-life design with even reduced inspection effort and life-cycle cost.

Damage as defined here is the detectable reduction of structural cross-section, resulting from either fatigue, wear or corrosion or a combination of them. It may be observed as a crack, a reduction in thickness or exfoliation. This observation can range from visual inspection to computer tomography, where ultrasonics and Eddy current being the methods mainly used.

The monitoring process as shown in Fig. 6 can be described such that a sensor being able to monitor any kind of physical parameter such as strain, vibration modes, acoustic waves, temperature, electrical resistance or whatever is positioned on the structural component. The sensor signal being recorded may be amplified, filtered and in any case analysed, which nowadays usually happens inside a computer.

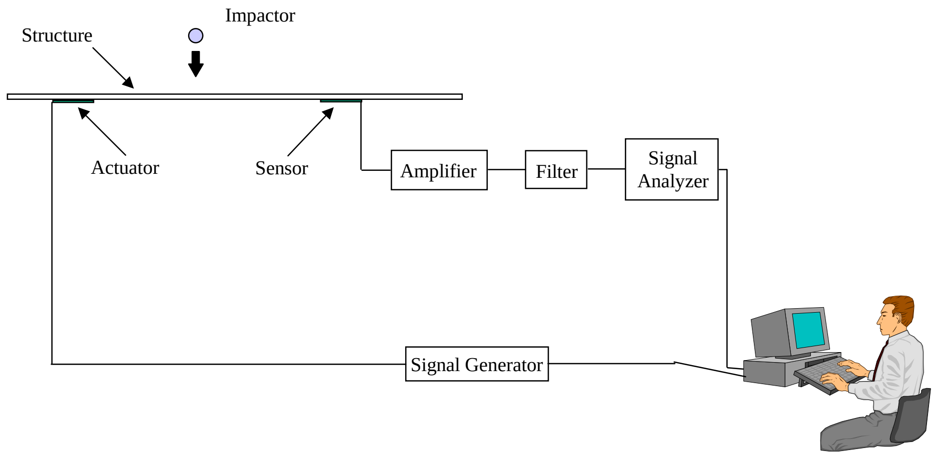

Fig. 6: The principle of structural health monitoring

Traditionally strain is monitored as a damaging load or as a change in the strain field, where in the latter case the strain gages have to be very close to the damage. Another is vibration modes, which turns out to be more sensible when the reduction in cross-section (e.g. a crack) is orthogonal to the stress induced by the vibration. A third option is acoustic emission, where stress waves are emitted from the damage when the structure is loaded. The efficiency of all these techniques is however dependent on monitoring the occurrence of the damaging event (e.g. load, impact, etc.). If this dependency should be avoided an actuation device needs to be added to the structural component, which allows a signal to 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.

An engineering design philosophy which has emerged over the past decade and which significantly also emphasises automated structural health and thus damage monitoring is smart materials and structures. Smart materials and structures – briefly spoken – is the adaptation or integration of sensing and actuation elements onto or into a structure or material, where sensing and actuation elements are linked via a controller. This sensor-actuator-controller combination can happen on a macroscopic (structure) as well as on a microscopic (material) level.

Relating this design philosophy to damage monitoring means that sensors and possibly even actuators are integrated or better even adapted to the structural component, such that non-destructive testing becomes an integral part of the structure itself.

For the sensing device virtually any type can be used as long as it is able to monitor the respective physical parameters being either generated by the load, damage or actuation device. So far fibre optic and piezoelectric sensors have been favoured.

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 Fabry-Perot based interferometer systems 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 actuators as well.

To easily adapt or integrate such a monitoring system onto or into a structure, the system has to be preinstalled on a carrier, such as a layer or a foil. A solution of this kind being denoted as a smart layer has been recently proposed and realised [3,4]. The layer (Fig. 7) consists of two Kaptone foils, with tiny piezoelectric sensors as well as the required electric wiring integrated in between, similar to the way this is done for electronic components. These layers are either integrated into a composite structure or patched on the outside of any kind of structure (e.g. metallic, polymer, composite, etc.). Smart layers can be configured such that they can be used for autonomously monitoring damage critical components. A software for generating the input and analysing the output signal is also provided.

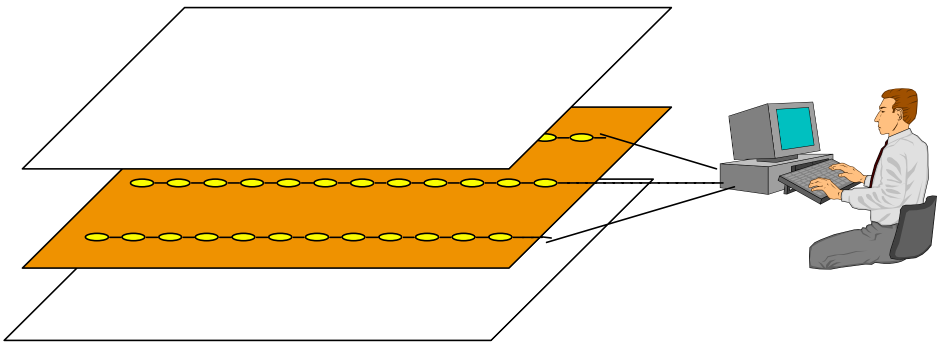

Fig. 7 Smart Layer Concept

Looking at what is currently happening in the development of materials on the microscopic level, this idea of the smart layer can be continuously improved such that the actuator/sensor functionality may be once configured on a microscopic level. Chiral or nanostructures are potential candidates being currently studied. Prior to this material development a substantial effort is however required in sensor signal processing, where some emerging approaches are described throughout the following.

Sensor Signal Processing Algorithms

Accurate information about possible damage in the structure requires intelligent signal processing which is one of the most important elements of any structural health monitoring system [5]. The overall intelligent chain of processing for a multi-sensor architecture is summarised in Figure 8. In what follows, different elements of this chain are briefly discussed.

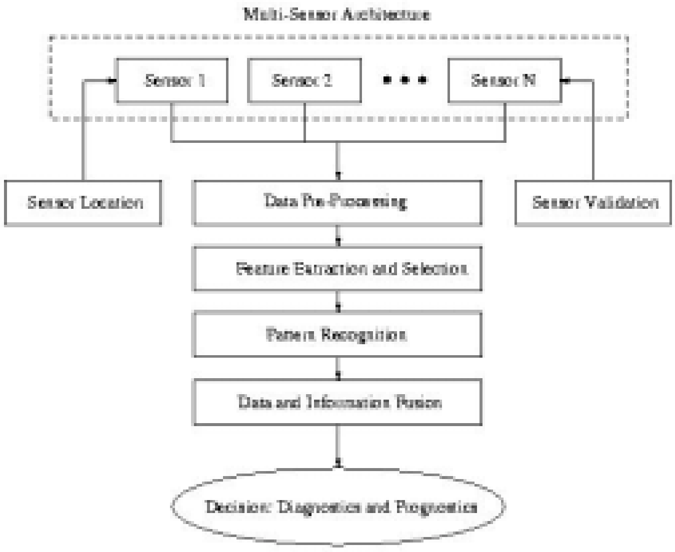

Fig. 8: Chain of sensor signal processing

Data Pre-Processing

Data pre-processing forms an important element of pattern recognition procedures for structural damage detection. It often includes smoothing and denoising procedures, normalisation, trend analysis and reduction of outliers.

The level of noise in the data can be reduced by local and/or global averaging. An alternative approach can be offered by smoothing and denoising procedures. Smoothing can be done using filtering or fitting. Fitting or the best fit polynomial through a data set is a smoothing process in which the number of fitted coefficients is usually much less than the number of analysed data points. There exists a number of low-pass filters which can be used to smoothen the data. This includes optimal smoothing procedures such as: the Wiener filter based on the Fourier analysis, and Savitzky-Golay, least-squares and digital smoothing polynomial filters [6,7]. More recently, denoising procedures based on the orthogonal wavelet transform have been developed [8]. Thresholding and/or attenuation can be applied to wavelet coefficients and remove the noise form the data.

The other pre-processing procedures are more or less related to removal of unwanted features from the data. Normalisation identifies relationships between measurements and features. Trends show unwanted temporal relationships in the data. Outliers are feature patterns which are statistically far from the normal selection of patterns used for training. They can lead to poor generalisation of the learning process. Outliers can be eliminated using standard statistical analysis.

Feature Extraction and Selection

Features are any parameters extracted from the measurements through signal processing in order to enhance damage detection. The choice of features involves a trade-off between the computational feasibility associated with low-level features and extensive pre-processing required for high-level features.

Feature extraction includes either signature or advanced signature analysis. Signature analysis employs simple feature extraction methods, based on data reduction procedures, which lead to scalar representations. This includes for example statistical spectral moments, physical parameters of the analysed system or modal based criteria. Advanced signature analysis uses sets of features in the form of vectorial or pattern representations such as: spectra, envelope function, amplitude of the wavelet transform. A number of advanced signature analysis procedures have been developed in the last few years, as discussed in [5]. This includes time-frequency and time-scale methods.

Feature selection is a process of chosing input for pattern recognition in order to reduce a number of features for training and therefore to reduce dimensionality of feature space. Often both terms feature extraction and selection are used synonymously. Also, the same procedures can be used for the process of feature extraction and selection.

Pattern Recognition

A set of features given by continuous, discrete or discrete-binary variables which are formed in vector or matrix representation is called a pattern. Patterns represent different conditions of an analysed structure. Therefore damage detection can be regarded as a problem of pattern recognition. Classical methods of pattern recognition use statistical and syntactic approaches [9]. Statistical pattern recognition assigns features to different classes using statistical density functions. Syntactic pattern recognition classifies data according to its structural description. In recent years neural networks have been established as a powerful tool for pattern recognition [10]. A number of different network architectures available for pattern recognition include: feedforward, recurrent and cellular networks. The architecture and process of training a neural network depends on which level of damage identification is required. An unsupervised scheme (Kohonen networks) offers a possibility of novelty detection. A supervised learning scheme (Multi-Layer Perceptron, Radial Basis Functions) is required for location and severity of damage. It appears that often simple unitary networks are not sufficient for complex pattern recognition tasks. In such cases network can be combined, using different ensemble-based and modular approaches.

More recently methods of novelty detection based on neural networks [11] and outlier analysis [12] have been established. These methods use a description of normality using features representing undamaged conditions and then test for abnormality or novelty. These methods provide only damage detection level, however they do not require any *a priori* knowledge about damage.

Data and Information Fusion

Different types of sensors can be used in a monitoring system such as for monitoring operational loads, which allow to establish the pattern of structural fatigue and in damage detection systems in order to obtain information about any possible structural damage. This can lead to multi-sensor array architecture. The multi-sensor architecture not only improves signal-to-noise ratio but also offers better robustness and reliability, and increases confidence in the results. Data gathered from different types of sensor often need to be combined with linguistic, knowledge-based information. There exists a number of different data fusion algorithms within hierarchical levels of processing. This includes [13]: physical models (Kalman filters, Maximum Likelihood, Least Squares), parametric methods (inference, Bayesian, Dempster-Shafer processing), information techniques (neural networks, clustering and voting methods, entropy measures) and cognitive-based models (knowledge-based systems, fuzzy logic).

Optimal Sensor Location

The sensor architecture requires not only appropriate sensors for monitoring but also their optimal number and location. This problem leads to different optimisation techniques. Many early optimisation methods, so called *ad hoc* methods, are based on rough and ready ideas without using much of theoretical background. Classical deterministic optimisation techniques can be classified into unconstrained and constrained optimisation. Simple deterministic techniques, like for example gradient based methods, are sufficient for local search, but for optimisation with several local minima they become inefficient. Constrained optimisation has a great degree of complexity, especially when nonlinear programming is used. More recently, new non-deterministic optimisation methods have been proposed. These are: neural networks, genetic algorithms, evolution strategies, simulated annealing, tabu search and different hybrids of the above techniques as reported in [5]. Application examples for damage detection include [15,16]

The mutual information which assesses the information content of random variables can also be used for optimal sensor location, as shown in [17].

Sensor Validation Procedures

Sensor architectures need to incorporate validation procedures which are important to detect sensor failures. There exist here two different approaches. In the active approach light may be sent in the case of fibre optic sensors through the sensor and the transmission characteristic of the optical fibre can be compared to the expected response using a novelty index. In the passive approach the response probability distribution of the sensor is computed. Subsequent measurements are then inspected to detect outliers which can indicate sensor failures. Most of the algorithms developed in this area are based on statistical analysis and neural networks.

Experimental Verification

Cracking in Aluminium Plates

The different ideas, methods and techniques described above are currently under a broad process of experimental evaluation. Such evaluations start with very generic tests like cracks in simple aluminium panels as shown in Fig. 9 and described in [20]. This 400x150x2 mm plate had a 1.5 mm crack which was initiated by spark erosion in the centre of the plate. The plate was fatigue loaded at 6 Hz with a load amplitude of $\pm$ 11.5 kN load amplitude and a mean load of 12.5 kN respectively. The plate was instrumented with 6 piezoceramic elements (PZT Sonox P5, 15x15x1 mm) fixed in a symmetrical configuration on both sides of the crack. For monitoring crack growth the acousto-ultrasonics method was used where the bottom right hand side piezoelectric element was used as an actuator. A Gaussian white noise with a maximum frequency of 25 kHz was used as an input signal.

The variance of the orthogonal wavelet coefficients was calculated for all wavelet levels representing data sets of two different sensors. The damage index was selected as the Euclidian distance between the mean vector of the logarithmic variance and the wavelet variance characteristics. The result of such an evaluation is shown in Fig. 9 as the logarithm of the damage index versus crack length. Here crack growth can be clearly seen for a crack growing from 6 mm onwards.

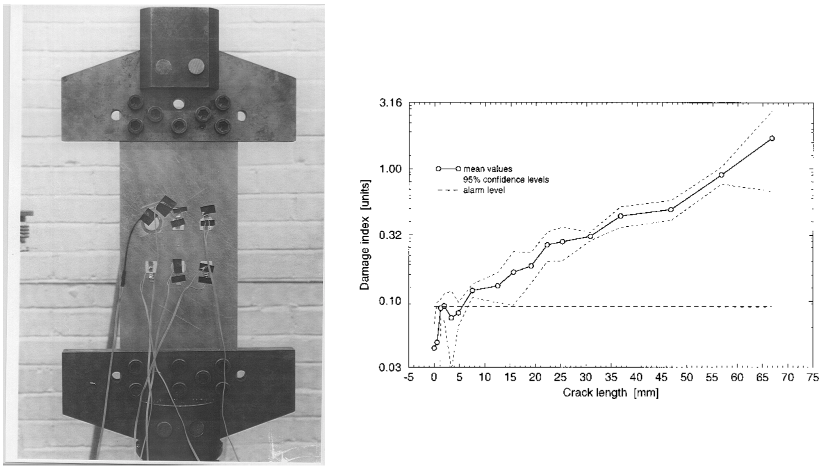

Fig. 9: Cracked aluminium plate and resulting wavelet based sensor signal evaluations

In another test a multi-riveted aluminium plate of 750x300 mm as shown in Fig. 10 was fatigue tested.

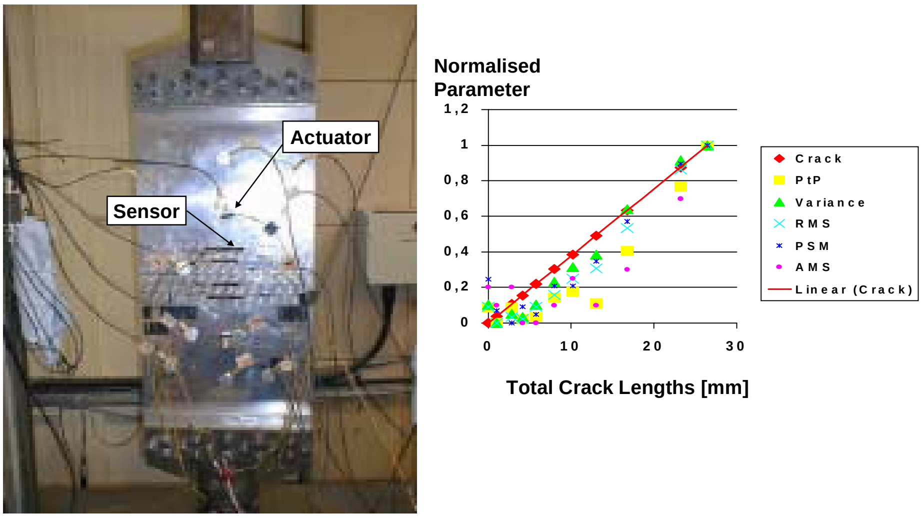

Fig. 10: Crack propagation monitoring in multi-riveted aluminium panel

Again the same type of piezoelectric element as mentioned above was placed as sensors between the rivet lines and as an actuator on the top, with the other sensors being classical acoustic emissions sensors used for benchmarking. The actuator input signal was now up to 500 kHz. Different parameters obtained from the time domain sensor signals have been evaluated, normalised and compared to the sum of crack lengths monitored visually, where the result is shown on Fig. 10. The closer the results follow the 45° line, the better the parameter considered which turned out to be best for the variance in the time domain signal.

Impact Damage in Composites

The damage location problem in composite structures was studied using a simple impact experiment [16]. The analysed structure consisted of a rectangular 530 x 300 mm composite plate and four aluminium channels. The top flanges of were fixed rigidly with screws to a measuring table. This box structure was intended to simulate the skin panel of an aircraft. A series of impacts was performed in order to obtain the strain data which was gathered using the piezoceramic sensors bonded to the structures. The neural network was used to locate impacts on the structure. Figure 11 shows the comparison between the actual and desired network output for the x-location coordinate.

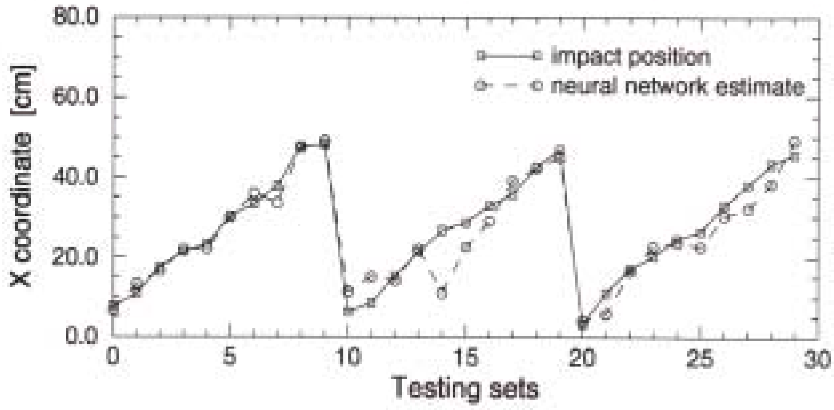

Fig. 11: Comparison between actual and desired network output

The techniques based on piezoelectric elements have also been applied for composite plates fabricated from carbon/epoxy T300/914 unidirectional prepreg which were mechanically fastened to a stiffening aluminium sub-frame and attached to a metal loading frame as shown in Fig. 12 [19].

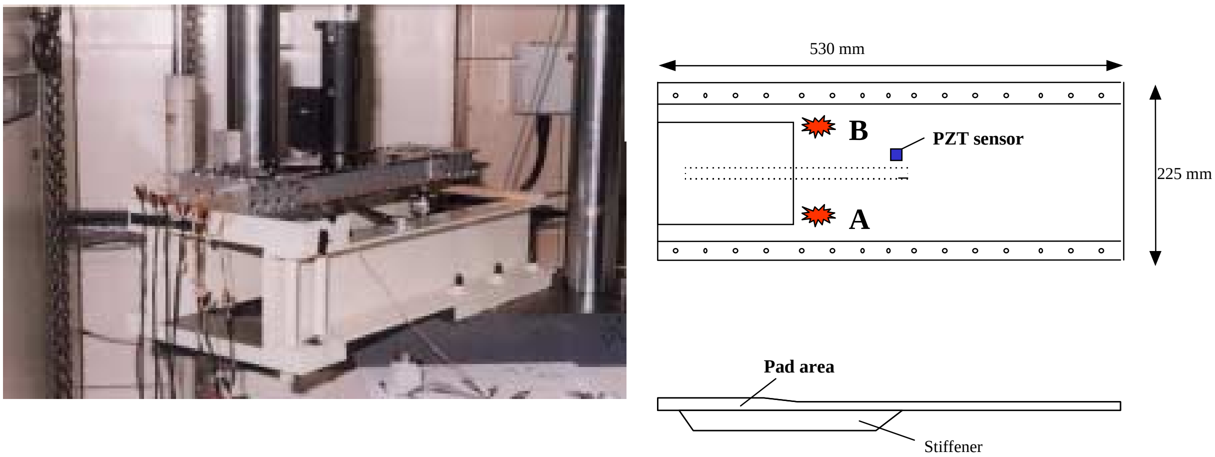

Fig. 12: Composite specimen with piezoelectric sensor

The piezoelectric elements were used to monitor impacting events. High-frequency strain data gathered were decomposed using the orthogonal wavelet transform. For the damaging impact energies at impact locations A and B clear spikes could be identified for the higher frequency wavelet decomposition. This spikiness of the data has been analysed using Kurtosis, which is a normalised 4^{th} spectral moment [21]. Fig. 13 gives the values of Kurtosis for the analysed impact signals for position A at different impact energy levels. A difference between damaging and non-damaging impacts can be clearly identified. The values for Kurtosis were also determined for the original time domain data where no significant difference could be seen for the different impact loads.

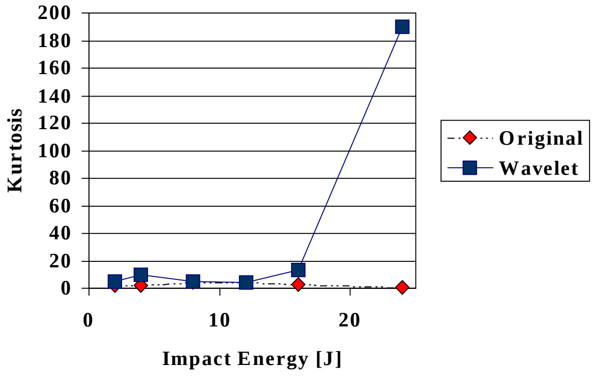

Fig. 23: Kurtosis characteristic for the impact strain data

Currently further testing is ongoing where the smart layer mentioned above is specifically used on specimens identical or similar to those mentioned above.

Conclusions

From the fact that the number of ageing aircraft is increasing, aircraft engineering has to deal more and more with extended aircraft operational life. When compared to the initial design, load profiles are more and more likely to change over an aircraft's life, which gives structural health monitoring rise of increasing importance. There is a definite need to obtain sufficiently reliable information on the status of damage or in other terms information on the portion of the structural life consumed. Only this information allows to perform aircraft fleet management, allowing to minimise the variance in fleet usage and perform timely on-condition maintenance. This information can so far only be obtained by estimating the consumed life on the basis of the loads having been monitored related to what is considered as the safe-life and thus crack-free portion. As soon as the safe-life period expires, extension of the operational life is only possible, when areas being prone to damage (the hot spots) are specifically monitored with regard to occurring damage such as cracking. Such areas are usually known from initial design together with experience gathered during in-service. Since monitoring with state-of-the-art NDT techniques may become highly troublesome, specifically when these areas are at very remote locations on the aircraft which require a large amount of dismantling, smart materials and structures such as of the smart layer type mentioned above become of a very specific interest, because they can be patched to these areas and contacted by wires or even a wireless system, thus avoiding the troublesome dismantling of surrounding components. Due to an often discovered lack in ease of structural maintenance on currently flying aircraft, this latter issue of monitoring can therefore become highly significant. A good example in that regard is the increased focus on integral designs which certainly reduces manufacturing and assembly cost but becomes highly troublesome with regard to repair.

The smart layer solution or any further emerging solutions in the context of smart materials are often easy to understand from the hardware point of view and look to be highly promising. A key issue with such monitoring systems is however actuator signal inputs and sensor signal outputs which require a thorough consideration with regard to signal processing, feature extraction and interpretation. There are solutions around which are in their early process of evaluation. The initial experimental results show that the algorithms being applied seem to be a good initial approach. However it is felt that there is still a significant potential to be explored in signal processing. This all together makes smart materials and structures highly interesting and promising already in recent proposals and solutions for condition based maintenance.

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