



NLR TP 97489

## **Aircraft structural health monitoring, prospects for smart solutions from a european viewpoint**

G. Bartelds

## DOCUMENT CONTROL SHEET

	<b>ORIGINATOR'S REF.</b> NLR TP 97489 U		<b>SECURITY CLASS.</b> Unclassified
<b>ORIGINATOR</b> National Aerospace Laboratory NLR, Amsterdam, The Netherlands			
<b>TITLE</b> Aircraft structural health monitoring, prospects for smart solutions from a european viewpoint.			
<b>PRESENTED AT</b> the International Workshop on Structural Health Monitoring, held Stanford University (USA), September 18 to 20, 1997.			
<b>AUTHORS</b> G. Bartelds		<b>DATE</b> 970901	<b>pp ref</b> 13
<b>DESCRIPTORS</b> Aircraft structures Aircraft safety Cost reduction Damage assessment Inspection			
International cooperation Piezoelectric transducers Smart structures Systems health monitoring Technology assessment			
<b>ABSTRACT</b> Structural health monitoring is an important safety factor in aviation that might benefit from advanced smart systems for damage sensing and signal processing. Current levels of structural safety and reliability do not present a particularly strong case for smart systems but cost considerations related to inspection and maintenance do. As an added benefit problems of poor accessibility and negative effects of human factors in inspection might be reduced. The implementation of such system requires development and demonstration by dedicated and qualified multidisciplinary teams, acceptance by aircraft designers, manufacturers and operators and approval by the authorities. Current European collaborative schemes and the associated funding in conjunction with an apparent interest among potential end users provide excellent prospects for the realisation of smart solutions.			



## **Summary**

Structural health monitoring is an important safety factor in aviation that might benefit from advanced smart systems for damage sensing and signal processing. Current levels of structural safety and reliability do not present a particularly strong case for smart systems but cost considerations related to inspection and maintenance do. As an added benefit problems of poor accessibility and negative effects of human factors in inspection might be reduced.

The implementation of such system requires development and demonstration by dedicated and qualified multidisciplinary teams, acceptance by aircraft designers, manufacturers and operators and approval by the authorities. Current European collaborative schemes and the associated funding in conjunction with an apparent interest among potential end users provide excellent prospects for the realisation of smart solutions.



## Contents

<b>1</b>	<b>Structural health and usage monitoring: why?</b>	<b>5</b>
<b>2</b>	<b>Structural health monitoring: how?</b>	<b>6</b>
<b>3</b>	<b>Options for smart solutions</b>	<b>7</b>
<b>4</b>	<b>Is there a case for smart solutions in aircraft?</b>	<b>8</b>
<b>5</b>	<b>European frameworks for development of smart technologies</b>	<b>10</b>
<b>6</b>	<b>Summarizing conclusions</b>	<b>13</b>

## 1 Structural health and usage monitoring: why?

Structural health is directly related to structural performance and in this respect it is a governing parameter with regard to safety of operation. This aspect of structural health is particularly relevant to transportation systems including their infrastructural elements and in this connection structural health monitoring is a **safety issue**.

At the same time a change in structural health may affect structural performance to a degree that remedial actions become necessary. Structural repairs increase the cost of transportation in at least two ways. First, the design and implementation of repairs implies *direct costs*. Second, the execution of repairs generally requires the transportation system to be temporarily taken out of service and this induces *indirect costs* due to the loss of production volume or as a result of leasing a substitute system.

To reduce repair and maintenance cost one might attempt to repair at a very early stage of damage development to limit direct costs. Alternatively, it might be decided to postpone repair until the transportation system has to be taken out of service for scheduled major overhauls to reduce indirect costs. In this connection structural health monitoring becomes a **cost issue**.

In case of the latter option (relying on the delay measure) it may be necessary to adapt operational usage to limit or even stop damage growth. If sufficient knowledge exists to relate damage rates to mission types this can be achieved by **usage monitoring**.

In general usage monitoring can be viewed as a valuable addition to structural health monitoring. Prescribed maintenance schedules are based on an *estimated usage pattern*. Knowledge of the *actual utilization* can be translated into a severity parameter that can be compared to the value corresponding to the estimated loading spectrum. In this manner prescribed inspection intervals and times between overhauls can be tuned to actual needs.

It is worthy to note that there are substantial differences in damage development and as a consequence in the manner structural health will deteriorate with time between metal and composite structure. Whereas in metallic components cracking is a gradual and predictable process with a high probability of occurrence the wear-out of a composite component as a result after loading environment is much less pronounced but composites may suffer from discrete traumas due to accidental damage of a non-predictable random nature. The situation suggests that different health monitoring philosophies should be applied to the two families of structural components.

## 2 Structural health monitoring: how?

Structural health, or equivalently, the state of damage can be established either directly or indirectly. In the latter indirect approach structural performance or rather structural behaviour is measured and compared with the supposedly known global response characteristics of the undamaged structure. If the effect of certain damages on structural response characteristics is known this approach provides an *indirect measure* of damage and of structural health.

In a direct manner one checks for the damage type under consideration, like cracks, corrosion or delaminations, by applying an appropriate inspection technique. These techniques, based on physical phenomena, in fact sometimes amount to response measurements also but in this case they have a very *local and direct character*. The established inspection techniques vary from visual inspection by the naked eye to passing the structure through a fully automated inspection gantry.

Obviously in both the direct and indirect approaches the **sensitivity** and the **reliability** of inspection are important quantitative performance measures. They are determined on the one hand by the laws of physics but on the other in practice also by the hardware and software quality of the inspection equipment and last but not least by the equipment operator: the inspector.

In this connection human factors like the loss of alertness in case of rare occurrences of damage and inspector fatigue in case of long and tedious inspections are important reasons to consider a smarter solution to inspection as an element of structural health monitoring.

### 3 Options for smart solutions

It is for both sensitivity and reliability that the particular features provided by **smart technologies** are considered.

Smart sensors could provide greater sensitivity provided that they are properly installed. This option is clearly related to specific inspections at precisely known critical locations that in addition may be poorly accessible. On the other hand, smart sensor systems with advanced data processing are relevant for inspecting larger areas for a variety of defects. If such systems function continuously the time between inspections is effectively zero and then a moderate sensitivity might suffice.

In a more general sense smart system design and smart interpretation and use of data generated by the systems are desirable features in any solution and in this context it is necessary to define what is meant here by *smart solutions* to structural health monitoring requirements:

*in the present paper smartness relates to either sensors for damage detection including their installation or to signal processing and presentation.*

#### 4 Is there a case for smart solutions in aircraft?

In the first chapter of this paper structural health monitoring was identified first of all as a safety issue. Certainly in air transport where structural failures may lead to fatal accidents the safety of operation is a prime consideration. Continuous research in the areas of fatigue and corrosion of metallic aircraft structure including inspection techniques (sometimes spurred and accelerated by dramatic accidents or incidents) has helped to achieve a very high level of structural reliability. Design for damage tolerance is now widely applied. It relies on a very profound understanding of material behaviour, on a very accurate description of the loading environment (both external and internal) all of this in combination with advanced manufacturing techniques and, of course, proven and reliable inspection and maintenance procedures. And in situations where brittle material behaviour or poor accessibility with regard to inspection are in the way of a damage tolerant design approach detailed numerical analysis supported by advanced testing has produced slow crack growth or safe life structure.

Any interest for automated integrated inspection systems could then result only from a need for greater **reliability of inspection**: the damage tolerance chain is only as strong as its weakest link which probably is inspection.

*It is thought that from a safety of flight position there is not a strong case yet for smarter solutions. Only in special situations an integrated sensor system may provide greater reliability than current methods. However, if in view of the rapidly growing air transport volume, expressed in billions of passenger miles flown, a significant reduction in structural failure rates is needed smart solutions may become more relevant as a safety issue.*

Another more important factor stimulating the development of smart systems, however, is the **cost of inspection**.

There is very little published data on the potential for cost reductions but the inspection efforts applied in current aircraft maintenance procedures are very considerable and moreover inspector training and motivation require continuous attention. It must be mentioned here that significant improvements have been achieved in traditional inspection equipment with regard to inspector friendliness and quantitative data presentation.

A recent study on inspection requirements for a modern fighter aircraft (featuring both metal and composite structure) revealed that an estimated 40 percent plus can be saved on inspection time



by utilizing smart monitoring systems. The situation at hand is illustrated in the table below.

Inspection type	Current inspection time ( % of total)	Estimated potential for smart systems	Time saved ( % of total)
Flight line	16	.40	6.5
Scheduled	31	.45	14.0
Unscheduled	16	.10	1.5
Service instructions	37	.60	22.0
	100		44.0

Another estimate derived for a fully automated impact sensing system for a composite structure, based on the use of integrated distributed piezo sensors in combination with advanced signal processing software arrives at a 50 percent saving on regular inspection time again for a fighter aircraft.

Admittedly, these estimates are based on data derived from laboratory demonstrators. They provide a drive, however, for the development of full scale demonstrators of smart structural health monitoring systems. In fact a major programme, to be discussed in more detail further on, recently got underway on the basis of the assumption that up to 20 percent of current maintenance and inspection cost can be saved in civil and transportation by the use of integrated on-line damage monitoring systems.

*So, the case for smart solutions to aircraft structural health monitoring requirements derives from cost considerations.*

The development of integrated automated damage sensing systems relies on different research disciplines and in addition it affects design and manufacture as well as operation and maintenance. As primary flight systems such as the airframe, landing gear or engines are involved the airworthiness authorities will have to be involved. Obviously, the development risks of smart systems are considerable and at the same time a broad acceptance among all parties involved is necessary to achieve implementation.

These considerations have led, in Europe, to a number of initiatives aimed at setting up collaborative research and development projects. Not only countries that have significant aerospace programmes but also smaller nations with advanced system component expertise are involved in projects that are described in the next chapter.

## 5 European frameworks for development of smart technologies

The European Unions Directorate General for Research has funded so called Framework Programmes for research and technology development and demonstration since 1987.

Currently, the fourth Framework Programme is underway and in the four years' time frame between 1994 and 1998 the European Commission will provide 12 billion ECU split between different areas as shown below.

Information and Communication Technologies	28 percent
Energy	18 percent
Industrial Technologies	16 percent
Life Sciences and Technologies	13 percent
Socio-economic research, cooperation with third countries etc.	10 percent
Environment	9 percent
Training and mobility of researchers	6 percent

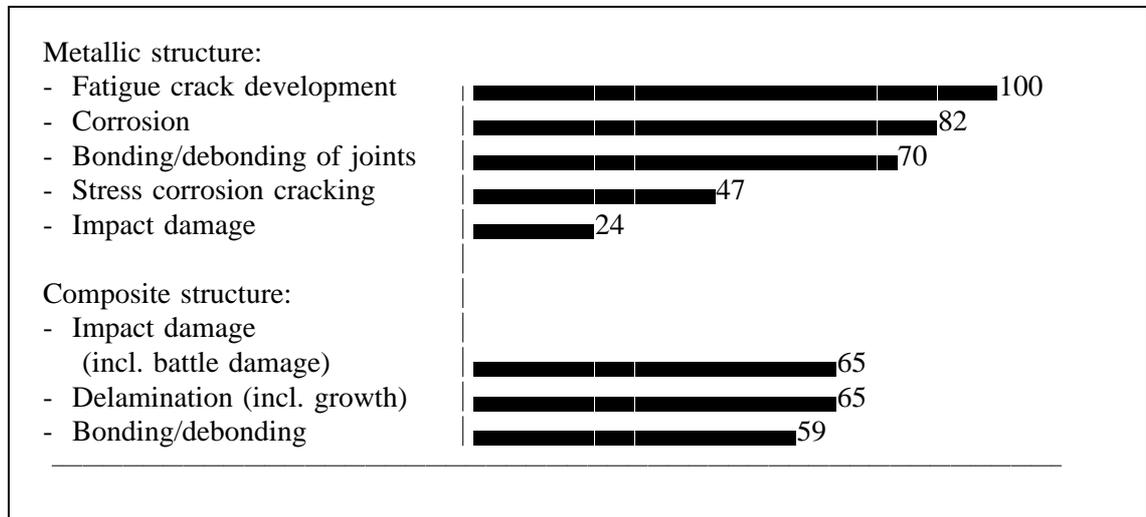
For each project the funding provided by the EC has to be supplement to the same amount by the contractors.

The programme on industrial (and material) technologies comprises an aeronautical chapter that addresses, among others, methods for improved operation and maintenance.

Under that heading a 4.7 MECU project was recently funded for the development and demonstration of on-line, integrated technology for operational reliability, MONITOR. A consortium led by British Aerospace and comprising all major Airbus and AIR partners as well as research establishments in aeronautics and optics from seven different countries will develop and demonstrate integrated automated systems for damage detection and for load path monitoring. The systems will employ fibre optic sensors as well as the more traditional acoustic emission or lamb wave sensors and they will be implemented in two full scale ground based demonstrators (a composite and a metallic structure). Further the operational load path monitoring system will be flown also.

The project team interacts with the potential end user community consisting of aircraft manufacturers and operators (including the maintenance firms). Very early in the project the end users were invited to respond to a questionnaire clarifying the monitoring options considered in the project. The contacts established will be maintained during the project by performing interviews with the more engaged parties and by organizing workshops and demonstrations as the developments progress.

The response to a first attempt to capture the end user requirements by questionnaire already allows a ranking of inspection targets that might benefit from smart solutions (see diagram below).



*Percentage of respondents with positive interest*

There is a very strong support for automated integrated inspection concepts from all sides, but the interest is based not only on the cost reduction aspects but also on the potential of performing automated inspection in poorly accessible locations and on the prospect of reducing human factor effects on inspection reliability.

The Western European Armament Group (WEAG) comprising all European NATO countries also stimulates research and technology development, in principle for defence purposes but it pursues coordination with the civil oriented programmes such as the Framework Programme 5 now under consideration. Its efforts are organized under a framework programme called European Cooperation for the long term in Defence (EUCLID).

WEAG currently develops Research and Technology Projects (RTP's) in a number of Common European Priority Areas (CEPA's). In the CEPA devoted to Advanced Structures and Materials there is considerable interest now in smart materials and structures. In 1995 an experts group with representation from five countries has been formed that is tasked with the identification of opportunities for smart applications to be developed in special RTP's.

The potential applications for smart materials and structures have been categorized as follows:

- Active adaptive vibration control.
- Structural health and usage monitoring.
- Shape control of airfoils and antenna's.



Workshops are held on all three subjects and the subject of structural health and usage monitoring will be covered at a joint WEAG-NATO workshop at The Hague on 7 and 8 October of this year. US participation is welcomed to broaden the coverage and to establish opportunities for coordination.

RTP's are organized by WEAG nations that contribute equal-value shares to the project and provide for financial coverage of their share according to national rules and regulations. Funding for individual RTP's generally is in the 5 to 15 million ECU bracket.

Finally, an important mechanism for research coordination formed in 1973 is GARTEUR, the Group for Aeronautical Research and Technology in Europe.

It aims to strengthen collaboration in aeronautical research and technology between European countries with major research and test capabilities and with Government funded programmes in his field. The group consists of six countries now and it is active in the following domains:

- Aerodynamics.
- Structures and Materials.
- Flightmechanics, Systems and Integration.
- Helicopters.
- Propulsion Systems.

An exploratory group has studied the current state of the art in smart structures and materials and has performed a cost-benefit evaluation of potential application in structural health monitoring. It has decided not to develop a GARTEUR activity in this field at this moment as the EC MONITOR project is running, but it will embark on an active adaptive vibration project as a precursor for a planned EUCLID project.

## 6 Summarizing conclusions

- Aircraft structural health monitoring is an essential element for continued safe operation. Current design capabilities and manufacturing and certification standards guarantee an extremely high level of structural reliability that can be maintained during the operational life of the aircraft provided that prescribed inspections are carried out, that data are processed and that remedial actions are taken when necessary. As a consequence, safety requirements do not contribute a strong case for advanced, smart, structural health monitoring systems with the possible exception of the requirement to limit the negative effects of human factors on inspection reliability.
- Both the direct costs of carrying out preventive inspections and the indirect costs associated with interrupted service, however, provide a strong stimulus for cost reduction programs. In this respect integrated damage sensing systems, advanced signal processing and maintenance oriented data presentation constitute smart solutions to inspection requirements that may reduce the cost of manpower for inspections and maintenance and at the same time increase reliability and enhance data presentation.
- Aircraft manufactures and operators have indicated that they would like to see more integrated automated inspection systems provided that they do offer a cost benefit and possibly are more reliable when compared to current inspection methods. They should not interfere with other flight systems and preferably be communicative to maintenance personnel.  
The authorities will accept such smart systems as long as they do not adversely affect current safety levels.
- Current international programs for the development and demonstration of integrated damage sensing systems for aircraft structural health monitoring in Europe provide the opportunity to achieve a breakthrough for existing technology towards actual application. The broad participation representing all the different key expertise needed, the obvious interest among the potential end user community and the financial support by international bodies are important assets in the current efforts to demonstrate and exploit smart health monitoring systems.