Structural Health Monitoring – A Design and Integration Issue

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ABSTRACT:

The structural health monitoring (SHM) process chain including solid state modelling, loads monitoring, fatigue life evaluation and finally damage monitoring is addressed in this paper. The problems arising from loads monitoring are discussed in terms of the sensor integration point of view and the complexity one can get in easily. The discussion goes further into the aspect of what to be defined as a sensor and what as a sensor system respectively and the interface between the sensor system and a complete engineering system to be monitored such as an aircraft. Finally some thoughts are elaborated regarding the incident when SHM should be implemented into an engineering structure. Most of the applications addressed are related to aviation.

INTRODUCTION

Much has been researched, written and published in the field of structural health monitoring (SHM) over the past decade. Examples of the major sources of publication include [1-9]. Most of the developments have and are currently still dealing with the development of sensors, monitoring of loads and damage, sensor signal processing and the SHM systems. A perspective is shown on how this SHM technology can come into application. Aerospace [10] and civil engineering including geotechnical hazards [11] are possibly the two areas being most addressed followed by marine, heavy machinery, power generation, railway and automotive. Looking at SHM for aerospace applications technologies are mainly at a laboratory stage and the question is: How can these technologies be integrated into the complexity of an aircraft system meeting all the safety and reliability issues related to this?

A major attraction with SHM is seen through the integration of sensors into the engineering structure. Synonyms such as comparing the engineering structure with the human body emerge, such as shown in Fig. 1 [12]. The synonyms can indeed lead to some inspiration but one needs to keep in mind that sensing in biology and sensing in engineering is of a significantly different character. While most of the sensors in biology are of a relatively primitive nature, posses a high degree of redundancy, are reproducible in the sense of self-healing but not replaceable and are highly networked, to just name a few of their features, sensors in engineering are highly complex, have a low degree of redundancy, are not reproducible but replaceable, and operate on very singular and as such not very much networked basis. Hence if one sensor in engineering fails the complete system can become very quickly impaired while when one sensor in biology fails this is hardly not even registered. Consequently the integration of sensors into structures is often not very much appreciated by operators of engineering systems such as aircraft since it will reduce the overall reliability of the system. Integrating SHM therefore needs a full understanding of the system's reliability, the engineering as well as the SHM system, such that the overall reliability of the system being possibly the major cost driver can be optimised.

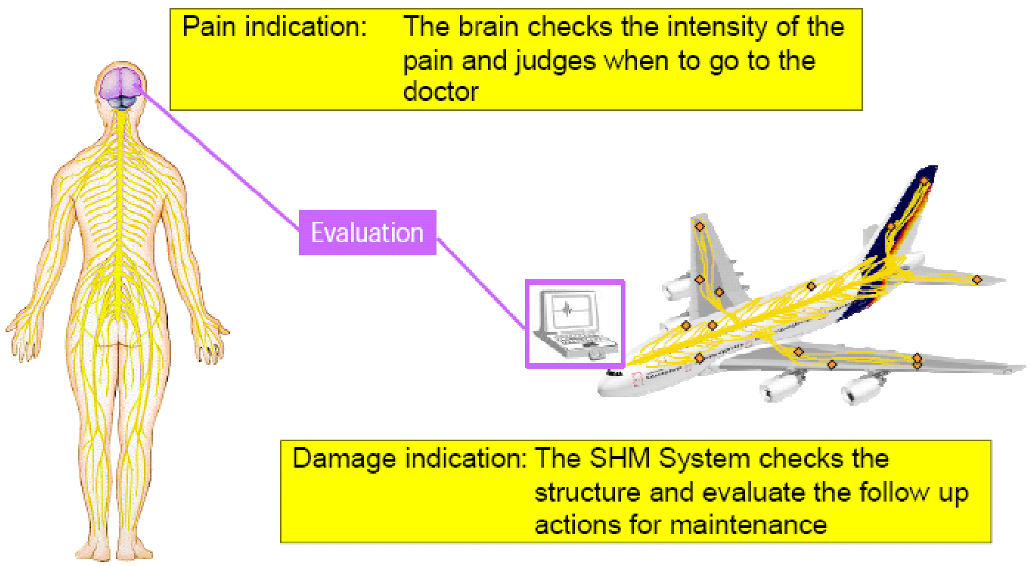

Fig. 1 An analogy of SHM according to [12]

The following chapters will try to address how SHM may have to be integrated into the engineering system design and realisation such that SHM can turn out to be beneficial in terms of cost and reliability.

DESIGN ISSUES

The design process of engineering structures consists of a variety of steps. It initially requires a solid state CAD model before it moves into the assessment of structural strength usually associated with FE modelling combined with the knowledge of the operational loads and materials' properties. This will then allow to know where damage is most likely to occur which will then define where damage should be monitored.

Many of our engineering structures today including aircraft and civil engineering buildings have been designed decades back in the past and are due to operate for decades still further in the future. One of the most remarkable examples in aviation in that regard is the US Air Force B-52 Stratofortress bomber. Would a component have to be replaced on such an old aircraft availability of a CAD or generally digital model would be most unlikely. Luckily this problem can be overcome these days as well as a follow-on structural assessment to be made which allows even a structure from the past to be adequately designed for future operations. The following paragraphs will describe this process along a structure being much simpler than an aircraft structure and are expected to demonstrate where the complexity of SHM integration has to be seen.

Solid State Model Generation

The engineering structure to be considered here is the frame of a mountain bike. Amazingly many of the mountain bike frame manufacturers design their frames mainly out of experience and do not possess any FE modelling as such. Fig. 2 shows how a CAD and finally FE model was generated using a laser scanning device. The laser produces a light stripe and scans the structure which is recorded by a camera and converted into a digital point cloud to be stored in a data base. The point cloud model is then subsequently converted into a polygon mesh, then structured on the basis of NURBS patches and refined as a CAD model that can then further be converted into an FE model.

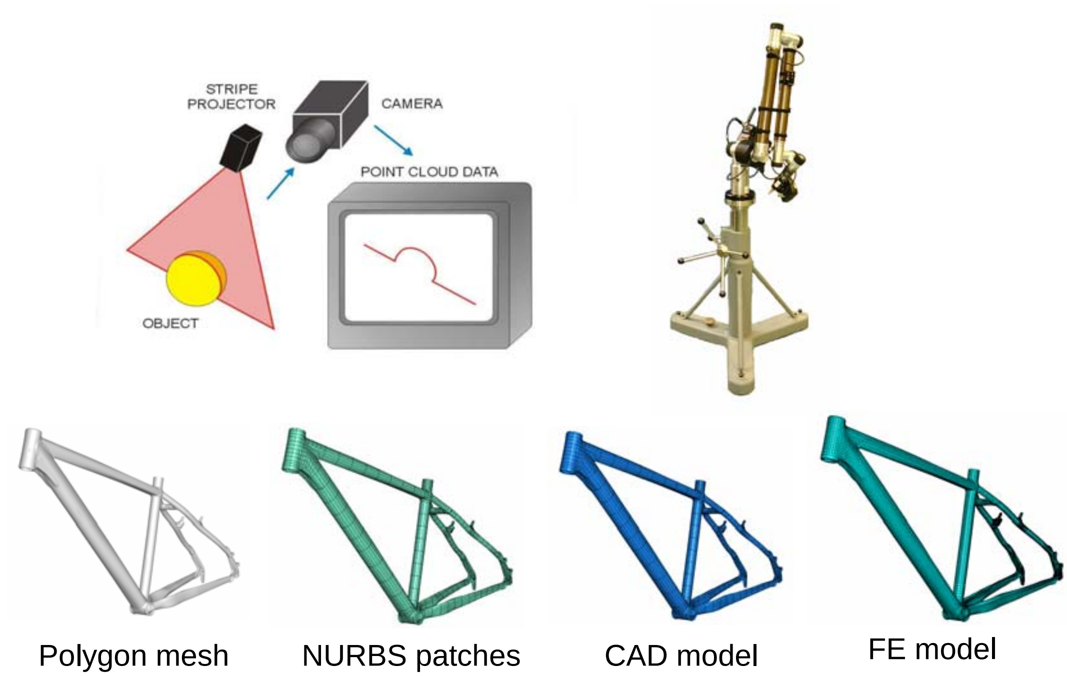

Fig. 2 Laser scanning of a structure and conversion into a CAD and FE model

Stress-Strain Analysis

To analyse the strength of a structure requires the knowledge of the loads to be applied. If those are not known to a sufficient degree they need to be determined. Finding the locations where this would be best done requires the FE model and some assumptions to be made with regard to the different loads to be applied. Fig. 3 shows the potential loads to be applied on a mountain bike frame. They look to be quite limited however a deeper analysis shows in what complexity one will be in. Fig. 4 shows the result for the pedal load case only and allows the locations of stress and strain concentration (highlighted by circles) to be determined at which a stain gauge for monitoring the pedal load sequence would be placed best. This exercise can now be performed subsequently for all the different loads applied on the bicycle frame individually and further superimposed with potential load combinations occurring in service. This will then allow a strategy to be developed on how to monitor the load sequence best being applied to the structure.

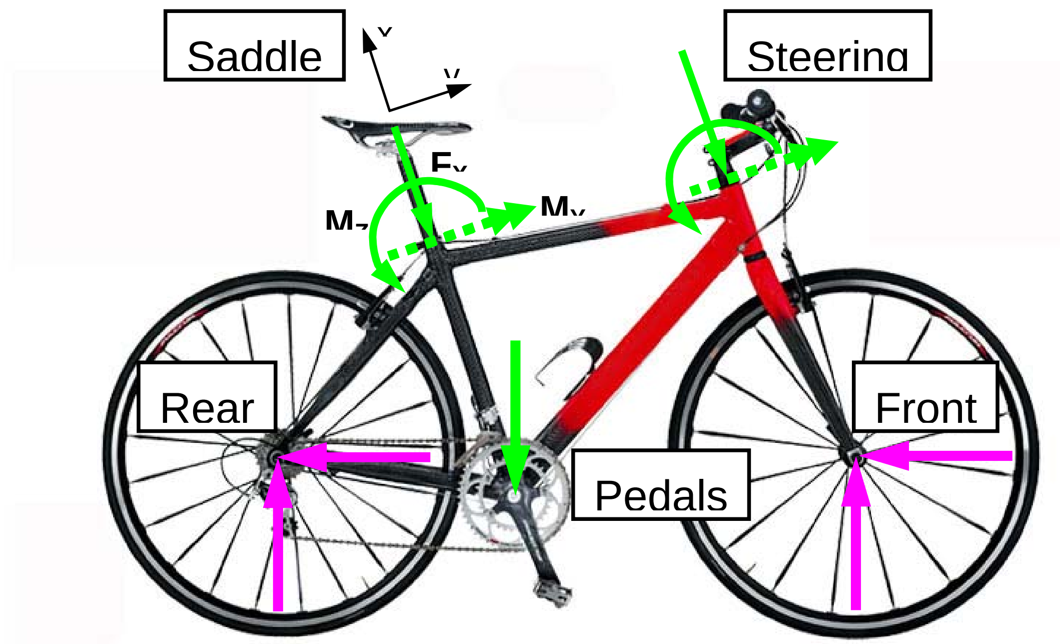

Fig. 3 Typical loads applied to a bicycle frame

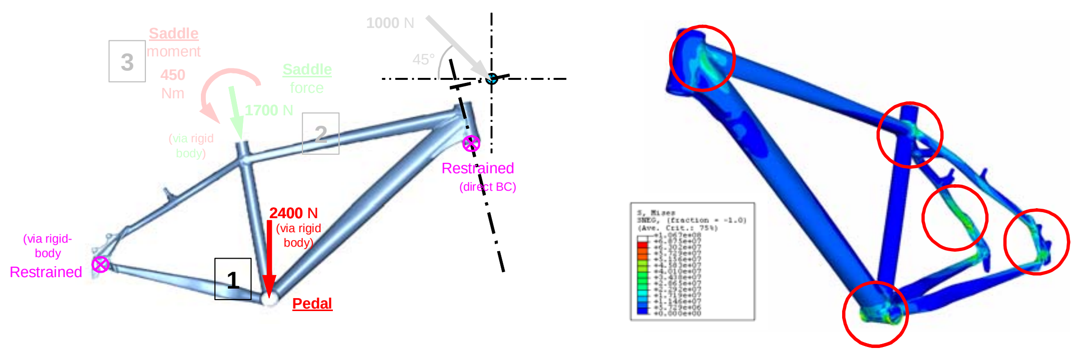

Fig. 4 Stress distribution on mountain bike frame obtained for the pedal load case

The limited number of 11 load cases and their combinations already shows that finding the optimal solution for a limited number of load monitoring sensors is by far a trivial problem. This among others makes it understandable why a complex aircraft such as the Eurofighter Typhoon has currently no more than 16 locations for loads to be monitored which makes it already a sufficiently complex problem. Strains being monitored can further be used for validation of the FE model and thus for further improvement of the assessment procedure.

Fatigue and Damage Assessment

The ability of monitoring a load sequence appropriately in accordance to the true operational conditions allows damage and thus the initiation of damage to be determined more precisely. Load sequences monitored as a time sequence can now be assessed in accordance to a rainflow cycle counting procedure which allows peaks and troughs of the time signal to be allocated to cycles characterised in terms of their mean stress and stress amplitude. Each cycle is then accumulated into a matrix describing mean stress over stress amplitude which is characteristic for the load spectrum applied. This matrix can then be again applied to describe a deterministic randomised in-service loading sequence of similar characteristic to the one having been monitored which in combination with a fatigue life evaluation post-processor allows damage accumulated in each of the elements of the FE-model to be estimated and thus also to predict the incident when damage is due to occur. Fig. 5 shows an example of such a component indicating the intensity of damage accumulated. This damage distribution map does indicate which locations are most likely to fracture and where the implementation of a damage monitoring system may be useful.

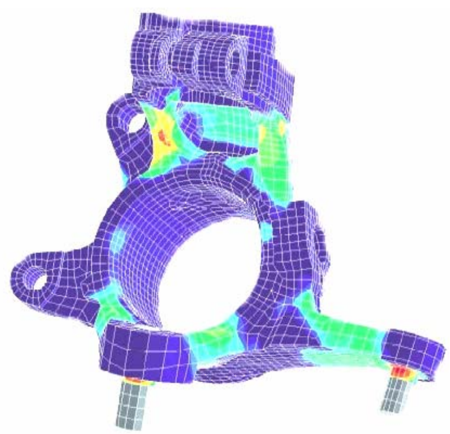

Fig. 5 Damage accumulated on a complex component using FE-Fatigue (Courtesy of nCode)

Damage Monitoring and Sensors Patterns

The knowledge of a damage to occur as described in the paragraph before and shown in Fig. 5 is not sufficient to simply bond some transducers that will act as sensors and possibly actuators respectively. What is also required is the knowledge along where damage (i.e. a crack) would propagate and what size of crack would have to be reliably recognised. This may be again associated with an increasing number of sensors which would be in contradiction to the reduced number of sensors and actuators requested by the engineering system operator such as an airline. Here some true current deficits of SHM become apparent. One of them is the lack of appropriate tools that allow the SHM process to be simulated. First approaches are provided in terms of using genetic algorithms and other optimisation procedures. However this is still far from being a holistic approach and tool allowing the monitoring process to be described and the number of sensors to be determined. Such tools would however significantly help to configure the appropriate sensor/actuator pattern.

Associated to that discussion is the discussion of what is a sensor by itself. Fig. 6 shows an example where a set of 12 transducers (sensors/actuators) are used in the form of the Smart Layer from Acellent Technologies [13]. These transducers interface with the Smart Suitcase which generates actuation data, records sensor data and may further process the sensor data in accordance to requirements being set. In the classical sense this would mean 12 additional transducers for monitoring the component considered, which may not be appreciated by an engineering system operator and may become further of an object for transducer optimisation and minimisation.

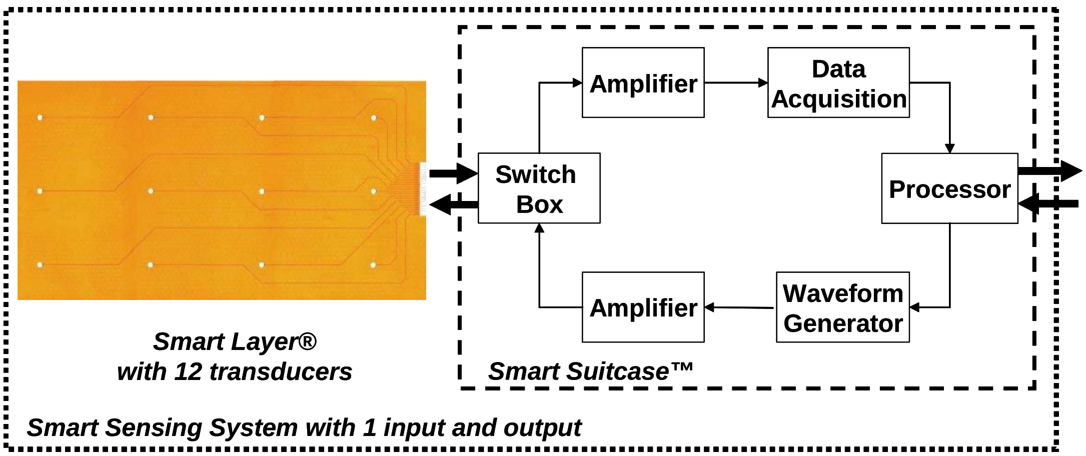

Fig. 6 Logic an interfaces of a sensing system for SHM

Indeed the number of transducers becomes irrelevant when the complete signal generation and processing unit becomes a part of the sensor system, in practical terms when the Smart Layer and Smart Suitcase from Acellent Technologies becomes a unity that can be considered as the smart sensing system highlighted in Fig. 5. This system now only has a single interface between the remaining engineering system, such as an aircraft, for which the requirements in terms of input and output as well as reliability can be clearly defined and controlled. Hence whatever is inside the smart sensing system is not relevant as long as the system meets the requirements set at the interface to the engineering structure or system. Problems of reliability and redundancy are therefore transferred to the SHM system supplier similar to the approach applied for any avionic or engine system in aviation. Virtually the biological analogy shown in Fig. 1 would be indeed applicable under these conditions provided the sensing system would meet the requirements accordingly.

INTEGRATION ISSUES

There are good reasons as to when SHM should be integrated into an engineering structure. For aerospace applications those can be well identified along the structure provided by the ATA Maintenance Steering Group MSG-3 document [14] of which an overview logic prepared by Boeing is shown in Fig. 7 [15].

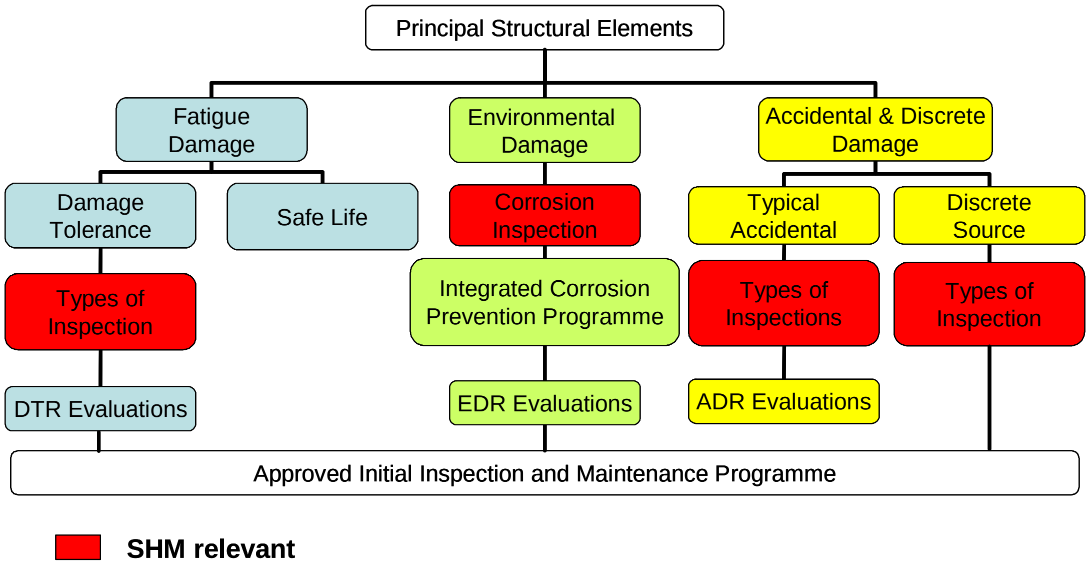

Fig. 7 ATA MSG-3 maintenance process logic breakdown [15]

Following that logic damage can occur either due to fatigue, environmental effects or accidental/discrete damage. Fatigue and environmental damage are usually effects which have been accounted for during design and which are less predictable at the conception of an aircraft. Most of their impacts are gathered from experience such as analysing the leaders of an aircraft fleet ageing over time. Hence it is possibly not relevant and even advisable to implement SHM for fatigue and environmental monitoring at the very beginning of the life of an aircraft since SHM would be without function over at least half of an aircraft's life.

However there are also good reasons for implementing SHM at the very beginning of an aircraft's life and this is when damages due to accidents have to be monitored. Of course not each type of accident can be predicted but there are different locations along an aircraft which are more prone to accidental damage than others and which are shown in Fig. 8. These include doors where access and delivery ground vehicles may collide under uncontrolled conditions or similar situations that may occur with respect to engine pylons in terms of ground vehicles circulating under the wings. Another more environmentally related damage is uncontrolled water spillage around galleys and lavatories. SHM systems are also very much advisable to be implemented from day one in an aircraft with respect to loads monitoring. This is nowadays becoming more and more standard with modern fighter airplanes [16] where load spectra can vary significantly. However this is also very much discussed these days in the context with commercial aircraft and here specifically in the context of hard landing monitoring devices [15]. Landing gears are possibly the most critical interface between the aircraft and the ground impact and are currently one of the major components for aircraft structural failure. So far judgement of the landing impact is left with the crew only but a more objective judgement would be beneficial in the light of the various landing gear failures that happened in the past.

There is another important issue with aircraft which drives SHM to be implemented into aircraft at the very beginning and not being related to MSG-3 which is the extension of the damage tolerance design principle in the way reported by Schmidt et al. [17]. The implementation of damage monitoring systems into structures, such as frames and stringers of a fuselage structure, being badly accessible for traditional manpower related inspection methods, could allow those components to be continuously monitored. This would permit the assumptions for damage tolerance design to be improved such that either inspection intervals could be extended or allowable stresses to be increased, the latter resulting in lower structural weight.

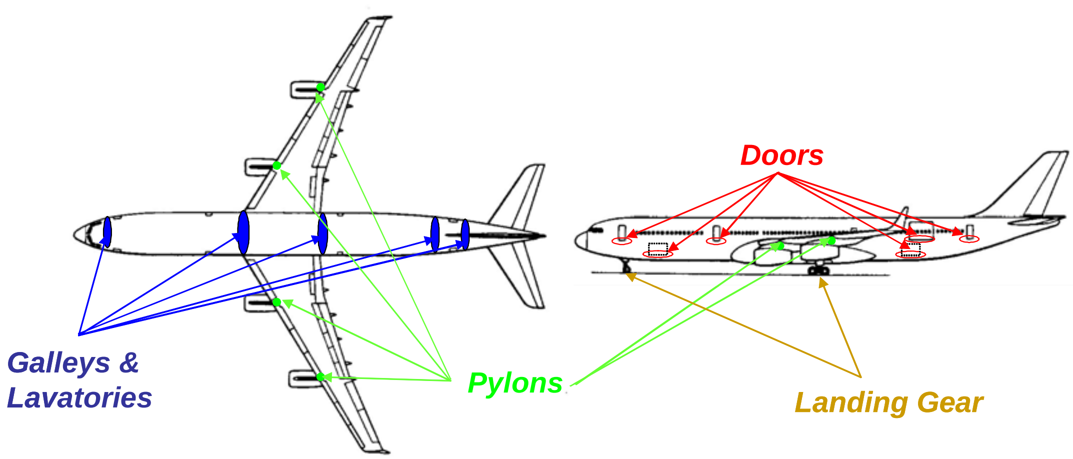

Fig. 8 Locations on aircraft for SHM to be implemented from the beginning

There is a further major issue which is related to the integration of SHM into the aircraft system which is the interface between the SHM system and the data management of the aircraft itself. Since automated monitoring is already done to a larger extent and for a longer period on engines and avionics there already exist standards and protocols related to data management at the interfaces between these systems and the aircraft. It will therefore be less than likely that these standards and protocols will be changed once SHM will be implemented. Hence the interface described in Fig. 6 is likely to be well defined from the aircraft's side. A view on those types of SHM integration issues into an existing aircraft platform is provided in Fig. 9 for a commercial aircraft [15] and in Fig. 10 for a military fighter airplane [18]. It should be kept in mind that the logic shown in Fig. 10 is already well in place due to the operational loads monitoring system already existing onboard the Eurofighter Typhoon [16]. Fig. 9 underlines the similarities of protocols and interfaces for engines and flight controls once SHM will be implemented.

BENEFITS

The rewards of implementing SHM have already been mentioned to some degree before. They range from saving weight through enhanced use of damage tolerance design to avoidance of gradual damage progressing due to accidental damage resulting in initial barely visible damage. These benefits have so far not been quantified but they can be considered to become significant.

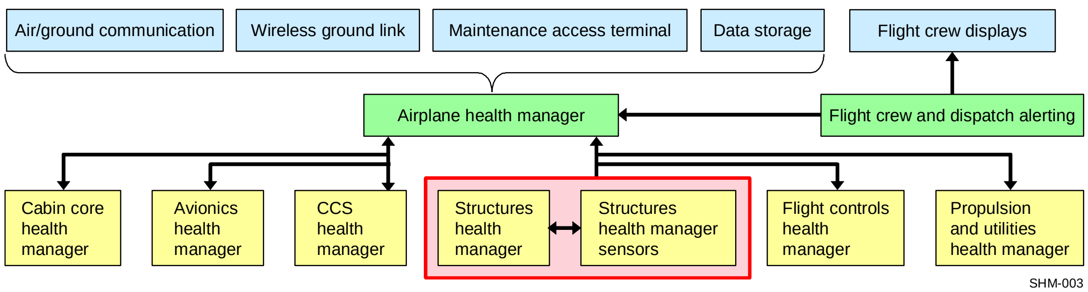

Fig. 9 SHM integration into the health management of a commercial airplane [15]

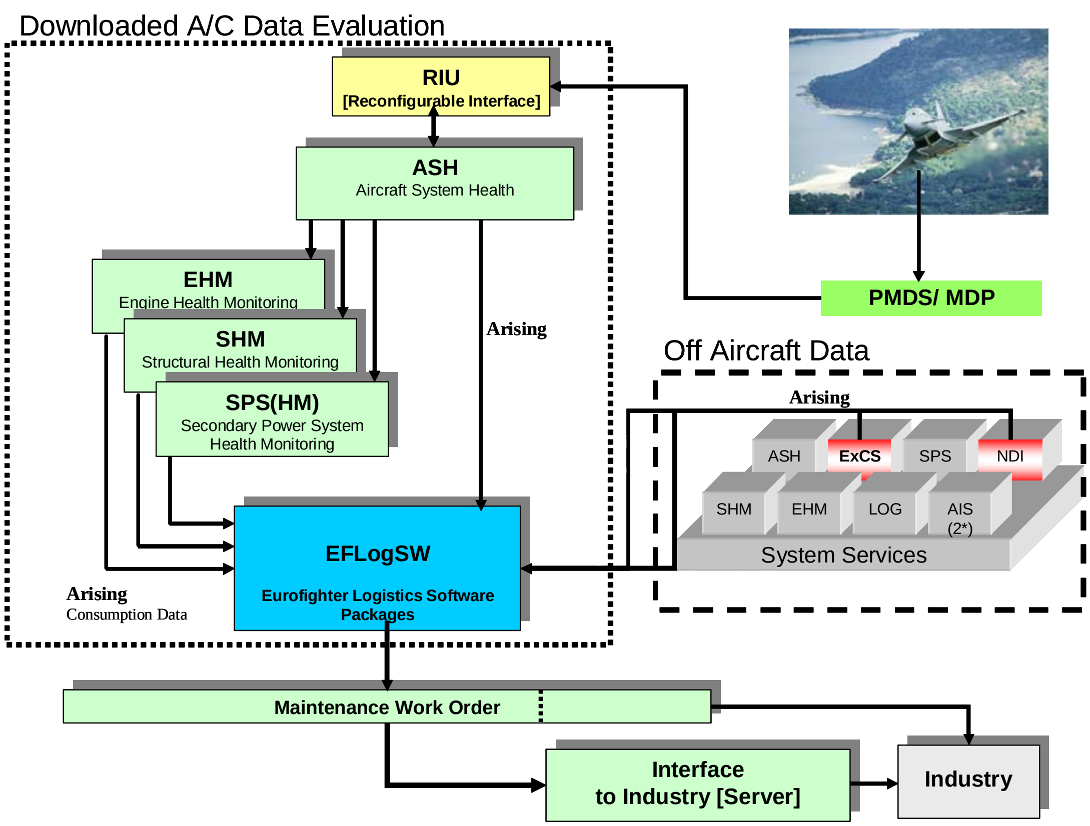

Fig. 10 Health management integration of the Eurofighter Typhoon [18]

Another aspect where SHM can contribute is aircraft operability. Many of the components to be inspected are located in areas highly hidden, where up to 99% of the inspection effort can be related to disassembly and re-assembly of components only. This effort could be avoided if an SHM system would be in place. This becomes specifically relevant if the component to be monitored is along the critical path of a maintenance process which becomes increasingly likely with the change from the flight hours based clearly defined letter checks to the more usage based and operator defined MSG-3 maintenance procedure where damage critical components can appear along the critical path of a maintenance process on a random basis. Keeping in mind that every hour of aircraft maintenance saved allows to increase an aircraft’s operability and that each hour of aircraft non-operation will cost the operator easily a remarkable four digit sum in US$ it becomes obvious that an SHM system may easily pay off in a relatively short period of time.

CONCLUSIONS

Designing engineering structures such as aircraft on the basis of SHM requires some care. All structural components requiring inspection have to be differentiated into two groups.

The first group includes those components where SHM is worth to be implemented from the very beginning. These are the components that may be prone to any sort of overloading or accidental damage as well as those where the information of their integrity can help to enhance the idea of damage tolerance and thus allow weight to be saved. Another type of sensor that contributes to SHM and which is worth to be implemented at the very beginning of an aircraft’s life is a loads monitoring sensor. Much care is required in finding the appropriate locations and combinations for these sensors such that the information generated can be well used for damage accumulation and damage initiation prognosis which will define when and where damage monitoring will have to be done.

The second group consists of those components which are prone to fatigue and environmental damage. These damages are not due to be expected before half life of the aircraft and as such the SHM system may not be advisable to be installed before. Furthermore there may be a variation in which components may have to be equipped depending on the past operational conditions of the aircraft.

The number of transducers (sensors/actuators) used for damage monitoring is not relevant when the transducers are combined with the signal generation and processing unit to a complete monitoring system and the monitoring system itself only possesses a single interface to the aircraft maintenance system. In that case the complete monitoring system can be considered as one single sensor and it is the reliability of the information transferred from the system through its single interface which contributes to the overall reliability of the aircraft. Since other monitoring systems for engines, flight control and avionics systems already exist it will be more than likely that the protocols used for those systems will also be applied for an SHM system hopefully operating in the not too far future.

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