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ASSESSMENT OF SENSOR TECHNOLOGIES FOR AIRCRAFT SHM SYSTEMS

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Abstract

SHM is a monitoring system which uses sensors, actuators and data transmission, acquisition and analysis, permanently integrated with the inspected object. The objective of SHM is to detect, localize, identify and predict development of fatigue fractures, increasing safety and reliability. This paper presents an assessment of sensor technologies used in aircraft SHM system. Due to the fact that most of these measurement methods are relatively new and still under development the present appraisal focuses on a number of parameters with reference to each method, including a sensor's installation issues, reliability, power consumption, sensor infrastructure, sensitivity and cost and availability. The work is predominantly focused on the assessment of permanently bonded sensors, such as foil strain gages, Comparative Vacuum Monitoring (CVM), Piezo sensors (PZT), Eddy-Current Transducers (ECT). Finally, all these methods are briefly discussed.

Keywords: SHM, sensor, fatigue crack, crack detection methods, usage monitoring

INTRODUCTION

A number of fatigue usage monitoring tools have long been in use to assure the optimal fleet utilization in terms of structural integrity. These tools differ with respect to the parameters they monitor and calculation methods they use. Some traditional monitoring methods may be quite simple while modern monitoring tools tend to be increasingly complex and sophisticated, combining software and hardware in one housing.

A tool most commonly used for monitoring aircraft usage is counting flight hours. This method is cheap and simple and needs no special equipment. The downside is that it is based on the assumption that each aircraft flies an identical load spectrum. This is far too big simplification for a reliable usage monitoring concept. This is why landing/flight cycle information can be additionally monitored. But this parameter applies only to landing and pressurized structures.

Since each aircraft is equipped with an accelerometer at a fixed nominal CG location, the N_z based tool was developed to collect appearances of N_z at fixed levels. It is important to note that only some parts of the structure affected by N_z can be monitored with this tool Time history is usually lost, and asymmetric loads are not considered. There are also difficulties in validating the data obtained and the transfer function between N_z and stress is not easy to elaborate for critical locations of complex structures.

A few decades ago a strain based monitoring tool was devised. This tool is relatively cheap, even if it needs an additional data acquisition unit and spread sensor's network. The ITWL has some experience of working with the prototype of a strain-based load monitoring system, its short-term installation and flight testing . In the latest project, several foil strain gauges have been collecting data from a trainer aircraft for two years now. The method allows for direct monitoring of chosen structure components. Flight data files are essential to estimate load spectrum for a specific aircraft. Despite the fact that strain gauges measurement left the laboratory quite long ago, still difficulties appear with data validation of complex structure. Harsh environmental conditions affect not only a recorder but the whole measurement and sensor system. Strain gauges require initial calibration carried out in several stages and periodically verified. Mission type, under slung containers, aircraft weight are variables in the measurement process. All in all, both the implementation of the system and post-processing of data are labor consuming operations.

In modern approaches, strain based tools are being adapted to multi-channel recorders as parametric systems gathering local load/strain information, flight parameters and in future (and possibly information from) all sort of other integrated sensors. The recorder's architecture is modular, made with high precision electronic circuit boards varying in type. The post-processing of collected data needs to be quite intensive and therefore it can be partly done in quasi real-time on board.

The latest parametric types of usage monitoring system is now the base for the development of next generation solutions. The most popular are OLM, HUMS and finally the SHM concept as a complex, integrated multi-sensor acquisition system.

CONCEPT OF COMPLEX USAGE MONITORING SYSTEM

Overcoming difficulties, the next generation of load and usage monitoring tools are being developed. Strain and load monitoring of aircraft structures have become well established concepts for determining components' lifetimes. Each new type of aircraft passes at least a short-term trial for operational load measurement – both at simulated and real flight hours.

OLM (Operational Load Monitoring) is a programme of limited duration, conducted to gain a snapshot of loads associated with operational use and is not used to directly life an aircraft. The objective of the OLM experiment is to validate aircraft analytical/numerical stress model.

HUMS is an ongoing activity that tracks and determines the life of aircraft and its components. The simpler and less accurate methods require greater margins of safety and result in less cost-effective utilization of life. Data acquisition in extended time is rather difficult to perform (periodical calibration, sensor reliability). Although this type of system is only being used by a small number of aircraft, it has become noticeably more popular in recent years.

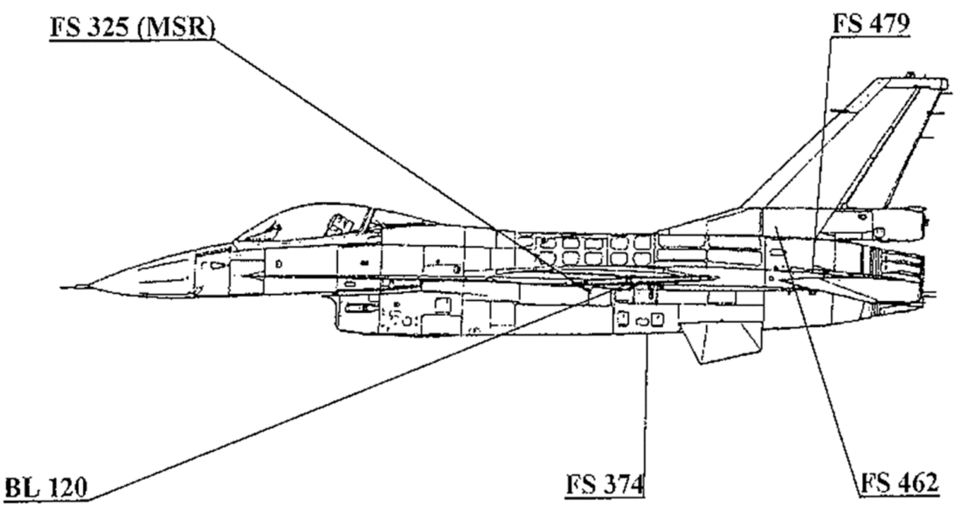

Fig. 1. HUMS sensor's location for F-16 NRLAF

Structural Health Monitoring (SHM) is an umbrella term for cutting-edge technologies using permanently attached sensor networks to enable continuous inspection of the reliability of structures. SHM for civil aviation is still in the experimental phase. The SHM concept is partly based on a number of different well-established NDT (Non Destructive Tests) techniques, such as ultrasonic inspection or eddy current methods. A modern SHM system has to satisfy the following conditions: airworthiness, satisfactory defect detection capabilities, cost efficiency and durability.

Producers and customers demand that a SHM system have about the same lifetime as that of an aircraft. This means that the sensor network should be as durable as the structure under investigation. A related issue is the challenge to address all the environmental conditions that occur during operation.

ASSESSMENT OF SENSOR TECHNOLOGIES

The present assessment takes account of the fact that sensor technologies differ with respect to physical phenomena they rely on and their capability of sensing structural damage. Different physical phenomena were used for a wide range of sensors. Their property to sense structural damage is also varied. Further technology details will be provided. The present assessment is mainly concerned with installation issues, types of multi-sensor infrastructure, and the reliability and sensitivity of a measurement method. Installation cost, availability and real-life system readiness is also taken under consideration.

Strain gauges

Strain gauges have long been in use including in pressure sensors, load cells, torque and position sensors. In aircraft structures, strain gauges are commonly used to determine load spectra of particular components. Sensors and resistors connected in a bridge configuration can successfully perform multi-direction local strain measurements.

The reliability of strain gauges is satisfactory, as proven by intensive utilization. Each sensor needs baseline calibration and scaling with a precision acquisition unit before it is ready for use. For long-term application, periodical recalibration is advised to estimate variable signal offset. It is a good practice to apply a sensor’s bridge configuration immune to the temperature gradient to increase the accuracy of measurement. Intensive signal value alteration can be observed as material displacement due to fatigue cracking.

As far as the assembling of sensors is concerned, strain gauges are characterised by a quite difficult installation process. It’s well known, but still several bonding-part problem can occur associated with the change of the material used (e.g. porosity, granularity) and the cleanness of the surface, type of glue, temperature and humidity of the surroundings. After mounting and drying, measurement lead wires must be soldered, and, subsequently, the initial bridge resistance should be defined. Befor connecting power leads, tests for shorting have to be carried out. Safety issues should be taken care of with respect to handling chemical solvents, neutralizers and adhesives.

The output of a strain gauge circuit is a very low-level voltage signal requiring a sensitivity of 100 microvolts or higher. The low level of the signal makes it particularly susceptible to unwanted noise from other electrical devices. Capacitive coupling caused by the lead wires' running too close to the AC power cables or ground currents are potential error sources in strain measurement. Other error sources may include magnetically induced voltages when the lead wires pass through various magnetic fields, parasitic (unwanted) contact resistance of lead wires, insulation failure, and thermocouple effects at the junction of dissimilar metals. The cumulative effect of such interferences can result in significant signal degradation. Therefore, when using strain gauges it is of utmost importance to apply properly shielded and adequate insulating coatings to avoid erroneous results.

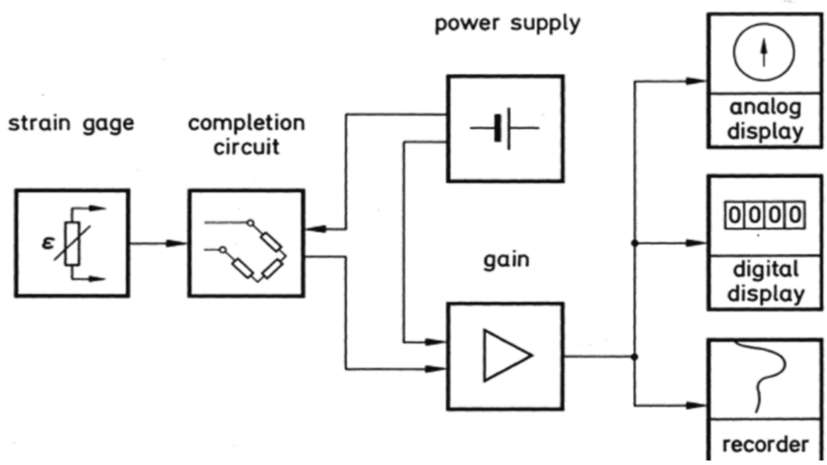

Fig. 2. Strain gage measurement circuit

CVM - Comparative Vacuum Monitoring

Comparative Vacuum Monitoring (CVM) offers an interesting method for in-situ, real-time monitoring of crack initiation and/or propagation. CVM is a measure of the differential pressure between fine galleries containing a low vacuum alternating with galleries at atmosphere in a simple manifold. These devices have been developed primarily for use in aircraft.

A variety of CVM sensor types have been developed for different needs. These include self-adhesive elastomeric sensors for the measurement of surface crack initiation or propagation and sensors integrated with the structure, for example between the faying surfaces of a lap joint. This flexible construction allows the sensor to adjust to the surface contours, including uneven surfaces and complex curves and locations where other sensors are difficult to install. CVM sensors are produced from a variety of materials to be better adjusted to the environmental conditions. CVM sensors are inert and may be left in-situ on a test object for real-time or periodic monitoring. CVM sensors can be fabricated in different gallery sizes in order to accommodate various sensitivity requirements. The installation process is similar to that of strain gauges, with protective coatings being the only difference.

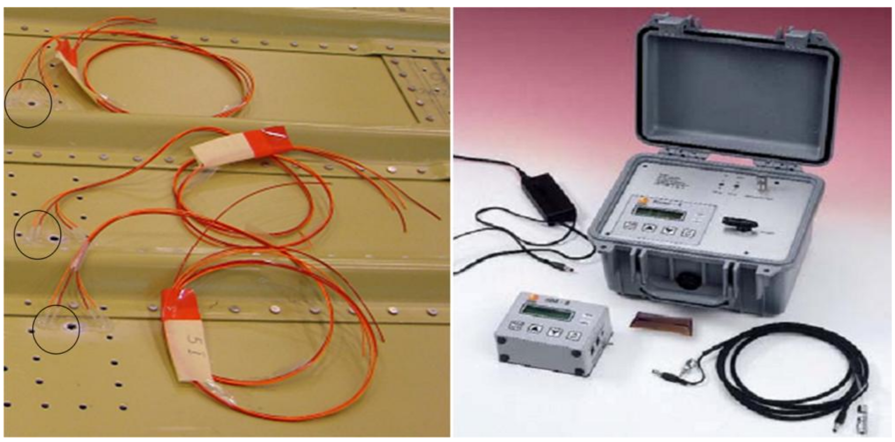

Fig. 3. CVM measurement system

To assess the long-term viability of CVM sensors in an actual operating environment, the sensors were installed, after extensive laboratory testing, on four civil aircraft for functional evaluation in the period 2004-2005. Altogether, 22 CVM sensors were installed. After a two-year-long validation program had been successfully completed, the CVM technology was included by

Boeing in its Common NDI Methods Manual. CVM sensor durability testing was also conducted by the Australian Defense Science and Technology Organization (DSTO) and Airbus. No loss in sensor functionality due to temperature, chemical or ultraviolet exposure was observed in these trials. This technique can be classified as an on-off sensor principle since a crack developing under the sensor induces a leak which is detected by a sudden change in the vacuum pressure. High strains that may accumulate and precede a crack cannot be detected by this technique.

Foil Eddy Current Sensors

ECT sensors have already found application in the aviation industry mainly for in-service inspections of aircraft layered structures, especially around fasteners, inspections of engine blades and inspections of wheels. Sensors for those applications are hand-held and manual scanning over an area of interest is performed by an operator.

Research is under way to develop flat foil flexible ECT sensors permanently mounted on aircraft (Fig. 4). These sensors can even be configured into arrays to cover larger areas and make possible electronic scanning of the inspected area. The copper winding is printed on the substrate, just like an electronic pattern. Flat foil flexible ECT sensors have great potential due to their thin geometry, they can be mounted on interfaces between structural parts; their topology can be tailored to many different part shapes (around the bolts, in corners, etc.); the connection can be part of the printed track and can therefore be also integrated, giving access to very remote places. Once mounted in hard-to-access places (or impossible to inspect locations), the sensors enable periodic readings that give information on the aircraft structural health. The configuration of an ECT sensor depends on inspection conditions as well as on the parameters evaluated. Sensors are designed and optimized in such a way that they are sensitive to local changes of the electromagnetic parameters of a tested structure due to the presence of a discontinuity. The method is very sensitive even to small cracks. However, it is an indirect method and needs calibration and reference signal prior to conducting measurements. It must be also noted that temperature, vibration and electromagnetic interference can all adversely affect measurement accuracy.

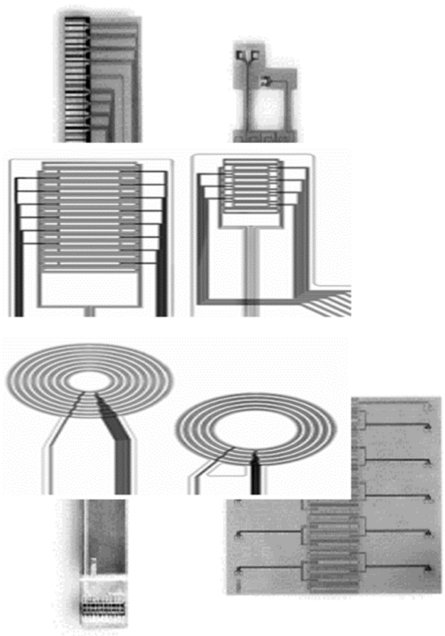

Fig. 4. Foil Eddy Current Sensors examples

Piezoelectric sensors

Piezoelectric materials can be used to measure stress and strain and can be also used to mechanically excite the structure to propagate stress waves and induce internal vibrations. Inputting a time-varying electrical signal to any of the actuators/sensors in a piezoelectric sensor network causes a propagating stress wave or propagating mechanical deformation to emanate from the sensor/actuator and travel through the material for detection by a plurality of neighboring sensors/actuators. Piezoelectric materials can be used in two sensing modes – active and passive, as illustrated in Figure 5. In Active Sensing Mode, the actuators are externally excited to generate pre-selected diagnostic signals and transmit them to neighboring sensors whose response can then be interpreted in terms of damage location and size or material property changes within the structure. In Passive Sensing Mode, piezoelectric sensors can be used as continuously monitored sensors that "listen" for external impact events.

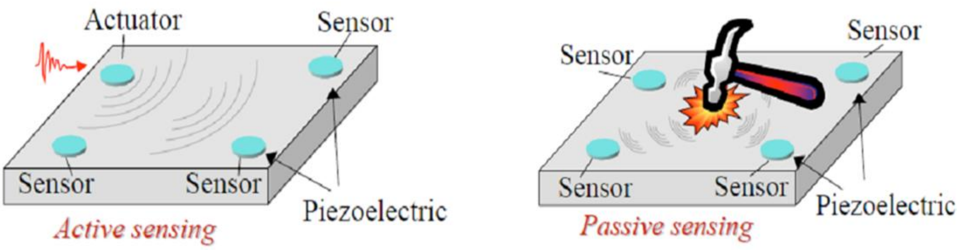

Fig. 5. Active and Passive Sensing Modes with piezoelectric sensors

Piezoelectric sensors are characterized by good tolerance of environmental conditions and long-term stability. Piezoelectric sensors do not require any special precautions since voltages and powers used to drive the sensors are low. Heat dissipation from the sensor should be quite small, too. The biggest safety concern is posed by possible short-circuiting due to sensor malfunction. The main disadvantage is associated with extensive post-processing involved in data interpretation.

SUMMARY

The paper presents the assessment of sensor technologies that can be used in aircraft monitoring system. An SHM system must have about the same lifetime as an aircraft. This means that the sensor network should be as durable as the structure under investigation. Installation, reliability and safety issues are discussed for chosen measurement methods. Each solution has its advantages and disadvantages, and the SHM system of the future should be tailored to specific user demands and system complexity.

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