CECAM

CECAM Bulletin C05-04

Structural Health Monitoring for Life Management of Aircraft

Principle Investigator(s): J. D. Achenbach, S. Krishnaswamy, and I. M. Daniel

Background

Research and development is proposed for structural health monitoring of aircraft components made of composite materials, specifically, graphite-epoxy laminates. The proposed work has three primary components: (1) investigate the evolution of fatigue damage and select a damage parameter; (2) select and employ suitable sensor technology to monitor fatigue damage; and (3) use the measured damage parameters in probabilistic failure analysis.

The failure sequence in composite laminates consists of matrix cracking, local delaminations, and, finally, fiber breakage. In combination with the experimental work, appropriate modeling will be used to define an appropriate damage parameter and a scalar damage function. Sensor technology suitable for permanent installation in or on composite components will provide the selected damage parameter as a function of the number of fatigue cycles. The measured damage, the probability of detection, the stress level and the damage growth characteristics will be incorporated in the probabilistic damage model, to calculate the probability of critical damage accumulation.

This project is expected to lead to a full-fledged application of structural health monitoring of composite aircraft components.

At Northwestern University we have significant experience with work related to the SHM of metal aircraft structures, including damage detection of a measurable damage parameter and the use of this parameter for growth prediction by a probabilistic fatigue damage procedure (Achenbach and Krishnaswamy), and with the study of degradation mechanisms and failure modes and their detection in advanced composites (Daniel). The proposed work will bring together the experience gained in these two areas for the development of structural health monitoring of composite aircraft structures.

Based on the experience of the present investigators, existing problems are expected to be surmountable for composite structures. The experience gained with metal structures will be invaluable in the proposed developments for composite structures. The main differences between the two developments are the character of failure mechanisms and the placement of sensors, primarily on the surface for metal structures and possibly embedded for composites.

This proposal will, therefore, be concerned with the following points of the request for work stated in the Solicitation:

Objectives

- Study and develop understanding of material degradation mechanisms and failure modes;
- Study and develop onboard sensing technologies;
- Study and develop sensor optimization and integration;
- Study and develop material prognostics;
- Validate and demonstrate health monitoring instrumentation and life extension methodologies;
- Train the workforce on health monitoring instrumentation. This will be done by our Senior Research Engineer, Igor Komsky, who has extensive experience in dealing with aircraft maintenance personnel.

Specifically, this is a proposal for a relatively small initiation project that should be seen as a precursor for a full-fledged project who's "GRAND PLAN" has the following components:

- permanently installed microsensors
- continuous monitoring in real time with known POD
- wireless transmission to a central station
- instantaneous interpretation of sensor data
- detection of unacceptable material damage at critical high-stress locations
- monitoring of evolution of material damage into critical size
- growth prediction by a probabilistic fatigue damage procedure
- adjustments for the actual damage state at prescribed intervals
- probabilistic forecast of lifetime.

Technical Approach

An intelligent health monitoring network should include a network of sensors to monitor several critical parameters that affect structural integrity. The sensors will need to function in an autonomous fashion and conform to stringent restrictions of size, weight, and power consumption. It is also desirable that the sensors be integrated with wireless telemetry for data uplink to a central processing unit. Where possible, the sensors should be either passive, or powered remotely.

A significant amount of work has been done in industry, national labs, and universities in the area of smart structural health monitoring systems. This work includes the use of fiber optic sensors, remote monitoring of electrical continuity of thin crack wires, embedded microsensors, embedded piezoelectric sensors, and wireless condition monitoring systems. The principal investigators are familiar with and have contributed to this body of earlier work [1-4]. The proposed work builds on these earlier efforts, and has three components:

1. Sensor Technology and Measurement Techniques
2. Monitoring of Evolution of Fatigue Damage in Composites and Selection of a Damage Parameter
3. Use of the Damage Parameter in Probabilistic Failure Analysis

Sensor Technology and Measurement Techniques

Sensor development: In this work, we propose to explore the use of microsensors and fiber-optic sensors for structural health monitoring of aircraft components. Microsensors are typically solid-state devices built on inexpensive silicon chips, or "coupons." These sensors can be distributed over critical regions of a structure. Such a coupon may contain a variety of microsensors for detection and cross-configuration of multiple defect signatures. The microsensors that will be investigated in this work include: wireless SAW sensors, and MEMS-based accelerometers and acoustic emission sensors. Wireless SAW sensors can be configured as temperature sensors, strain sensor, and with appropriate modification, as flaw-sizing sensors and acoustic emission sensors. Fiber-optic sensors that will be considered include Bragg-grating sensors for ultrasound and acoustic emission monitoring. The emphasis in this work will be on identifying useful applications of such microsensors for condition monitoring of aircraft components, and to select appropriate sensors and systems of sensors for both in-flight and maintenance facility condition monitoring.

A significant part of the project will be concerned with testing of sensors for detection of microscopic damage and quantification of damage and fatigue cracks that evolve out of damaged zones. Acoustic emission sensors will be used to passively monitor damage formation and fatigue crack initiation and growth. These sensors will be complemented by SAW sensors for active interrogation of the damaged zone for quantitative measurement purposes. Figure 1 shows a typical configuration of SAW sensors for sizing of damage and surface breaking cracks. Both SAW sensor arrays can serve as generators and receivers, and the sensor response can be tailored to be sensitive to the flaw size.

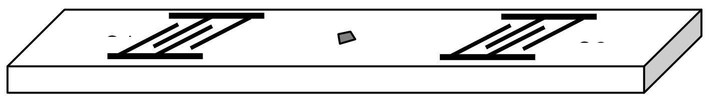

Figure 1: SAW sensors for flaw sizing

Placement of sensors: A related issue that needs to be addressed is the determination of the optimal location for placement of sensors. Sensors can be placed on the exterior of structures, or for composites, they can be embedded. Sensors should be distributed at structurally critical locations and optimized for sufficient sensitivity to monitor incipient failure. For this, the critical areas of flaw initiation need to be identified, and appropriate acoustic emission and SAW sensors should be installed in such locations. At the same time, it is essential that sensors do not adversely affect structural integrity.

Interpretation of sensor data. Measurements must be interpreted correctly and accurately to characterize damage in complex structures. Sensor data obtained will be used as input to the probabilistic failure models discussed in section 6.

Monitoring of Evolution of Fatigue Damage in Composites and Selection of a Damage Parameter

The objective of this task is to characterize and monitor the damage mechanisms and damage evolution in composite laminates and select a damage parameter relevant to the fatigue life of the part.

Under quasi-static loading the failure sequence in composite laminates consists of matrix cracking in the transversely loaded plies, matrix cracking in the axial (longitudinal) plies, local delaminations at the intersections of these sets of cracks, and finally fiber breakage at ultimate failure.

Use of Damage Parameter in Probabilistic Failure Analysis

Probabilistic failure methods will be applied in conjunction with structural health monitoring so that damaged components can be identified and repaired or replaced. Quantified measures of reliability (provided by probabilistic methods) allow maximization of inspection benefits through optimization of the health monitoring technique.

A systematic approach to reliability assessment for a structural component containing damage is illustrated in Fig. 7. As can be seen from the figure, the underlying concept in developing accept/reject criteria for a component is based on detecting and characterizing damage and evaluating it in terms of failure mechanics and a damage growth law. The aim is to determine whether damage in a structure will be sufficiently small that failure can be precluded with a high degree of certainty within a preset time interval.

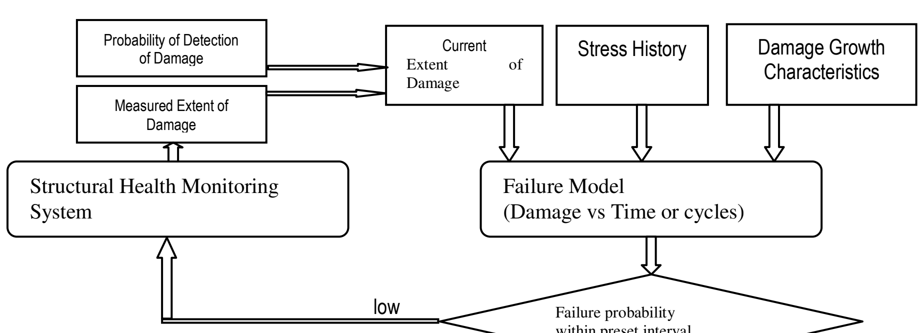

Fig. 7: Flow diagram of a structural health monitoring system

Plan of Work

To demonstrate proof-of-concept in the first phase of this project, we propose the following plan of work.

- select a material and geometry: Laminated Graphite Epoxy
- set up fatigue tests
- instrument the specimen with sensors
- define damage parameter to be measured
- collect sensor data on-line
- verify damage off-line
- define damage functions
- apply probabilistic fatigue procedure
- probabilistic forecast of lifetime
- verify result

The understanding gained in this work will set the stage for health condition monitoring combining fatigue reliability assessment and inspection methodologies for aircraft components, and will provide important guidelines on computational efficiency requirements for the reliability assessment in relation to sensor efficacy and the processing of sensor data.

In a second phase of the project, the focus will be directed toward actual aircraft components. These components will be selected in consultation with engineers from the aircraft industry. The general ideas outlined in this study, suitably adjusted, will be applied to specific components.

Interaction with Industry

The PIs have ongoing interactions with personnel at the Phantom Works Group of Boeing, St. Louis, in the area of Structural Health Monitoring. Preliminary discussions with that group have provided valuable input into this proposal. Boeing has indicated that they will be willing to provide guidance and assistance (including providing composite specimens) for this project.

Expected Outcomes

The outcomes of this feasibility study are expected to be:

- A better understanding of emerging sensor technologies that are key to the development of in-flight health monitoring systems.
- Improved sensor reliability and transition of the technology to implementation transportation systems.
- Demonstration of applicability of sensors to fatigue damage monitoring.
- Direct and real-time use of data in structural reliability assessment.
- Integration of sensor data into probabilistic fatigue damage models for assessment of residual life
- Training of graduate students and other engineers in a challenging technology that is vital to the future of US aviation efforts.

The initiation phase of this project (first 12 months) will be considered successful upon the demonstration of the feasibility of using reliable sensors for acoustic measurements on sample specimens, data interpretation and the use of data in life-time prediction. The goal for the second phase of this project (2 and 3 years) will be demonstration on real aircraft components, and the transition of lab technology to full-scale implementation and commercialization, with subsequent application of the technique to achieve improved aircraft safety.