Electrical Conductivity Tomography as Health Monitoring System for Thermal Protection Systems

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Abstract

For the goals of improving mission reliability, increasing safety margins and reducing life-cycle cost, Health Monitoring in aerospace applications becomes an emerging technology leading to the development of systems capable of continuously monitoring structures for damage with minimal human intervention. Health Monitoring Systems (HMS) are designed to cover related and overlapping fields such as condition monitoring of machines and structures, structural integrity assessment, damage detection and structural failure prevention.

HMS can be distinguished in systems which are active during operation (operational) and in ground-based systems (non-operational). On-board, real-time sensing systems are applied for operational HMS to solely monitor structure conditions during the flight (passive HMS) or even to reduce or repair the detected damage by actively taking counter-measures (active HMS). However, the latter is more one of the future main objectives of recent investigations and researches in HMS. Non-operational HMS instead are expected to make pre-flight and maintenance inspections more automated, more reliable and much faster than human inspections.

Because of the harsh aerospace operating environments and the constraints related to the mass budget, HMS sensors must be able to withstand these extreme conditions, while having minimal size, weight and power requirements. Various approaches of Health Monitoring Systems in the field of aerospace technology have already been performed. For all of these approaches a large amount of sensors are required in order to perform real time measurements on the structure which has to be monitored. The sensors have to measure numerous parameters, e.g. temperature, mechanical loads, pressure etc.

The following structural sensing technologies are under development at the moment: fibre optic sensors (FOS), active and passive acoustic sensors (piezoelectric sensors), micro electro-mechanical systems (MEMS), electrical resistance measurement systems, nano-tubes, wireless sensor systems based on radio-frequency identification devices (RFID) and non-contact sensor systems, such as laser vibrometry, shearography, laser ultrasound and infrared thermography. However, most research on HMS technologies for aerospace applications is concentrated on fibre optic sensors due to numerous advantages such as low complexity, low weight and their immunity to electromagnetic interference.

Another promising sensing method is the electrical resistance measurement technique, which is barely investigated up to now. This method benefits from the advantageous qualities of self-monitoring materials, such as carbon fibre-reinforced polymers (CFRP). They can sense their own strain and damage by measuring their electrical resistance while having a large sensing volume, great durability, low cost and a simple design since no embedded or attached sensors are required.

A literature survey about general information as well as recent developments and investigations of Health Monitoring Systems (HMS) technologies will be displayed. Thereby, not only HMS for aerospace applications were considered but also HMS applied in various fields, e.g. aeronautics, civil engineering etc. Sensing systems found in the literature are for instance fibre optic sensors,

piezoelectric sensors, wireless sensor systems and electrical resistance measurement systems. An explanation of some of the found HMS is done briefly in the document. For all the identified HMS technologies a Technology Matrix is defined, including the assignment of TRL levels.

Within the scope of the gathered information, a HMS concept feasible for hot structures in aerospace applications was defined. The HMS concept is based on the variation of the electrical resistance of electrically conductive materials, e.g. such containing carbon, in case of local damages. Previous investigations clearly prove that cracks and delaminations of CFRP panels can be detected by recording the electric conductivity or resistance, respectively. Obviously, applying this method to materials where the matrix is also electrically conductive, unlike CFRP panels, is a much more difficult task, but nevertheless, the HMS concept is feasible.

Two possible approaches for the determination of the electrical resistance of graphite or C/C-SiC or C-SiC material samples have been identified. Since the HMS concept must be feasible for aerospace applications, it is necessary to identify the role of the temperature in the variation of the electrical conductivity of materials containing carbon in order to identify only the change of the conductivity caused by the damage of the material. Therefore, the facilities chosen to perform the measurements must heat the material sample to the desired temperature. It is suggested to conduct the resistance measurements of the probe in a resistively heated graphite tube with a cavity available at the IRS. This facility is usually used for emissivity measurements of material samples and it can be heated up to relatively high temperature (2000°C) [1]. The measurement is performed in an inert argon atmosphere in order to prevent the oxidation of the graphite. Furthermore, an assessment of performing measurements of the electrical resistance of material samples in a plasma wind tunnel is given [2].

Tests are performed with 12 material samples, six of which are C-SiC samples, provided by EADS Astrium, and six are graphite samples. Three tests were not successful. The tests in the pasma wind tunnel show a general behaviour of the electric resistance over the temperature, which is not in full agreement with published data. This difference is accounted to the plasma influence. The plasma environment has obviously some non-negligible effect on the resistance. Conditionally, it can be assumed that the plasma environment shifts the minimum of the electrical resistance of carbon containing materials with respect to the temperature. Results from the graphite measurements and C-SiC measurements do not allow a clear statement on which direction of the temperature scale the shift occurs, since the two results indicate opposite directions. Therefore, more tests are needed here in order to investigate this point.

A comparison between baseline samples and samples with artificial damages shows that there is a difference in the electrical resistance distribution over the temperature, indicating that the general HMS concept is feasible for hot structure applications. Due to relatively large errors and noise, a more quantitative statement cannot be given at this point. It is recommended to perform additional test campaigns with improved test setups. The noise is especially problematic when measuring graphite samples, since their electric resistance is relatively low. However, the overall values are consistent when they are compared with the rarely available literature data. Moreover, for the C-SiC measurements in the plasma wind tunnel a trend is visible showing a slight increase of the absolute resistance values when having increased (pre) damage. In addition, there seems to be a move of the maximum of the curves to lower temperatures with increasing damage.

For the graphite samples the absolute resistance values are significantly smaller- as expected. Within the comparison with the EMF-based measurements verification for the applied methods can be derived despite of the fact that histories of the resistance curves in the plasma wind tunnel seem to have a behavior that is influenced by the plasma environment.

The measurement chain has proven extremely sensitive towards the contact between the electrodes and the sample, where by slightly increasing the pressure of the electrodes the resistance would change by one order of magnitude. Applying springs does solve the problem only partially, since the thermal heating of the springs destroys their elasticity. Many difficulties, if not the most of them, will be avoided if the electrodes are embedded into the samples. The fidelity of the results and the comparability would be much higher. It was also experienced that the EMF is not well suited for these tests, since the space restrictions are to great. The plasma wind tunnel probe used here proved to be very well suited. It is water cooled and hence the test setup is not exposed to very high temperatures. Another challenge is the electric insulation of the sample from the probe. Here, Boron-Nitride (BN) was used, which has the limitation of operating at temperatures higher than 800℃ only in inert atmospheres. During this test campaign the BN was exposed to temperatures up to 1700℃ in nitrogen plasma. In case of air plasma, BN will not be possible. The problem of the insulation is important because for applications on aerospace structures, the electrically observed structure, meaning the structure of which the resistance is being observed during operation, must be insulated from the rest. Questions arise concerning the mechanical strength of the insulator at the interfaces and its operating temperature range. BN has very low mechanical strength and limited operating range with respect to the temperature. Therefore, another suitable material needs to be identified in the future.

An additional great challenge of the HMS concept is the change of electric characteristics of the carbon or graphite due to its thermal history. Various authors have found out that the crystalline structure of the graphite changes irreversibly when exposed to high temperatures. This means that for re-usable structures the HMS concept cannot deliver exact data after the first operation of the structure, since the behavior of the electric resistance might be different from the first time. Accounting this change to significant mechanical defects of the structure will presumably be very difficult, if possible at all.

The TRL of the HMS concept based on the observation of the change of electrical resistance has been lifted to TRL 5 according to the general TRL definition for technical hard- and software (source Acquisition Operating Framework, UK Ministry of Defence) or to TRL 4 to TRL 5 according to the NASA TRL definition respectively. An additional test campaign with the improvements proposed here is necessary to consolidate TRL 5, while a breadboard of a relevant hot structure might be tested in a plasma wind tunnel in order to reach TRL 6.

The study at the whole and the experimental set-ups are summarized in references [3, 4]. Moreover, the paper will give recommendations for future work.

Further Literature:

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