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Durability and Self-Testing of Sensor Bondings used in Structural Health Monitoring

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Abstract
Structural health monitoring systems can be considered as a network of permanently installed sensors monitoring the state of the structure. If material degradation occurs, it is self-evident that the sensor as well as the connection between sensor and structure must be more durable than the structure itself. This aspect of SHM systems appears up to now a little bit underestimate, but it might be a real bottle-neck if these systems come into practice.

Keywords: Structural health monitoring, durability, electro-impedance, aerospace

1. Introduction

Structural health monitoring (SHM) targeting the automated inspection of the state of aircraft structures typically consists of a network of permanently installed sensors equipped with facilities for data recording and advanced data analysis [1]. It is a prerequisite that, if material degradation takes place, the connections between sensors and structure must be more durable than the structure in the endangered zone itself. This aspect of SHM systems appears up to now a little bit underestimate in the literature because frequently, only idealised laboratory conditions are present. But a lack of awareness on the real full-scale conditions will be an important bottle-neck if these systems will come into practice. The considering of real operational conditions might even result in the rejection of alleged promising technologies. Finally, aircraft producers and customers demand that the lifetime of SHM systems must be in the range of the lifetime of the aircraft itself, typically more than 30 years [2].

There are numerous external conditions influencing the lifetime of a sensor network. A number of them, especially chemical contaminants (dirt, hydraulic oil, electrolytes) can be shielded by efficient coatings, such as the enclosure of sensors in mastic material. However, a certain group of external influences cannot easily be shielded. This regards in the first place the mechanical loading and the stress exerted by temperature and temperature gradients. The present paper wants to show some examples of the activities within the European project AISHA in establishing different set-ups for testing the durability of sensor connections with a special focus on self-testing capabilities under in-service conditions.

2. Selection of methods for the assessment of sensor integrity

The paper focuses on the use of ultrasonic transducers and optical fibre sensors. In all cases, the sensors were attached by adhesive bonds. Therefore, sensor testing is in those cases equal to bond testing. However, also the integrity of the sensor itself might be a challenge [3], but the described techniques are also able to give information on such defects.

Quantitative classical bond testing is frequently destructive [4]. However, it lies in the nature of the tests required for SHM applications to find technologies that are non-destructive. The main target of the measuring programme is thus to combine the test of sensor integrity with self-testing capabilities that would be required under in-service conditions. Beside ultrasonic bond tests (vibration, transmission, pulse-echo) other techniques were proposed for non-destructive bond testing, such as electrical impedance, thermography and x-ray [5]. The disadvantage of such techniques is that the quality of the bond can only be tested for parameters (such as the homogeneity of the adhesive layer) for which no quantitative relationship with the remaining bond strength is available. This is a serious disadvantage. On the other hand, the bond between structure and sensors does not experience the full load that typically exists between e.g. lap joints or other structural connections. Therefore, the information obtained from non-destructive bond testing might be sufficient (see e.g. the broad application range of the Fokker bond tester).

2.1 Ultrasonic signal transmission test

A potentially strong indication on the quality of the sensor adhesion is the determination of the amount of transmitted energy, in our case expressed by the root mean squared (RMS) value (see e.g. Fig. 4). If the sensor is broken or if the connection of the sensor with the structure is disturbed, a decrease or even a disappearance of the signal will occur (see e.g. Fig. 5). This means however that the signal transmission technique is only appropriate to check sensor integrity if no real defects are present. Otherwise, it might be difficult to distinguish between a damaged sensor bond and a structural defect. For these cases, a modified testing scheme must be in place. An interesting option is the use of reference transducers for which the sound path between actuator and sensor is outside the zone prone to material degradation (already applied within the project AISHA to slat-tracks of an Airbus A320).

2.2 Electro-mechanical impedance test

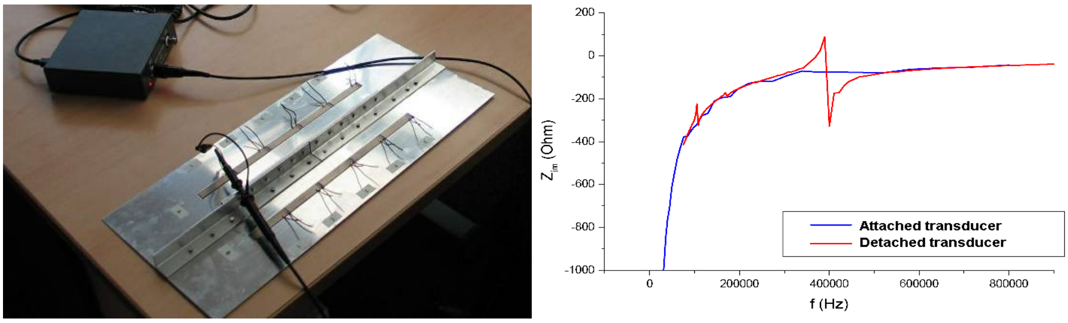

Fig. 1 left side: Impedance analyser (C60 - Cypher Instruments) to check ultrasonic transducers at a model panel with stiffeners – right side: Impedance spectrum with attached and detached transducer

This test, familiar to the method used in the Fokker bond tester, was proposed for SHM applications by e.g. Giurgiutiu and Zagrai [6], and it requires additional equipment, v.a. an impedance analyser. The results obtained might be more reliable than the signal transmission test performed without reference transducers. The electro-impedance method is based on the fact that the electro-mechanical impedance of a piezoceramic sensor depends on the strength of the adhesive bond. Due to the adhesive bonding, resonance frequencies of the piezoelectric crystal are (partially) suppressed, and there is a characteristic impedance spectrum representing the properly glued sensor connection. If the sensor connection starts to fail, the electromagnetic impedance will also change, and the sensor will approach the characteristic resonance frequencies of a free oscillator (Fig. 1, right side). This technique should be independent of diverse kinds of structural defects which are located far enough from the transducer. But the impedance also “feels” the surrounding of the structure where it is glued on, and in this case, if the material failure is close to the sensor, this technique could deliver ambiguous results. In that case, electro-mechanical impedance is even a candidate for alternative SHM applications (Impedance Damage Detection, [7]).

In practice, the sensors connection should be checked by a proven combination of ultrasonic signal transmission test, electro-impedance tests, and the reliability of the information can be enhanced by using a redundant amount of reference transducers which are located outside the range of maximal stress and strain.

2.3 C-scan of bonds

If the case of optical fibre sensors attached to composite plates, different techniques for assessing the sensor durability have to be applied. C-scan offers the option for an assessment of the adhesive layer by through transmission or pulse-echo techniques. The quality of the adhesive bonding is proven when the transmission parameters are not changed.

3. Piezoelectric patches on an aluminium sheet

3.1 Set-up and adhesives investigated

To perform the tests, actuators and sensors were attached on aluminium plates using different adhesives, such as M-Bond 200, Loctite Hysol EA 9309 3NA or PC-12 Kyowa. A special attention was dedicated to the careful surface preparation such as required in the respective specifications sheets. The actuators were driven by an arbitrary waveform generator (GAGE – waveform generator) at a frequency of about 400 kHz. The signal consists of Hanning-windowed bursts (10 counts at an output voltage of $10V_{pp}$). The signals were received by a piezoceramic sensor and processed without pre-amplification. A GAGE card was used as an AD receiver and

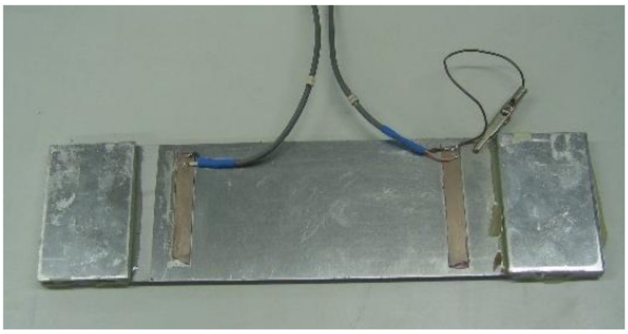

Fig. 2 Typical set-up with an aluminium sheet, adhesively bonded and wired PZT transducers and end-tabs for the static and dynamic fatigue tests

there was a bandpassfilter (300-500 kHz) applied. The signal was recorded with a sampling rate of 5 MHz. The whole set-up was controlled by a home-made Labview programme.

3.2. Behaviour under mechanical stress

The sensor and the sensor connection can partially be shielded against a number of external conditions, such as the chemical environment. The shielding against mechanical stress is much more difficult to achieve. The first possibility is avoiding the implementation of sensors at positions where high dynamic and static loads and strains can be expected.

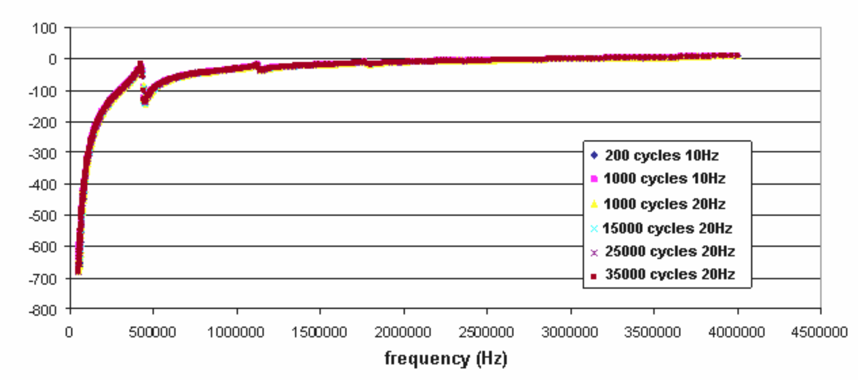

Fig. 3 Electro-mechanical impedance of the PZT transducers as a function of the number of load cycles. The fatigue tensile tests were performed with the parameters shown on the plot and F_{min}-F_{max} = 4kN - 12kN

Using the set-up shown in Fig. 2 the stress related durability of the sensors was tested. For this case, the aluminium sheet was equipped with transducers and end-taps and it was fixed in a dedicated test bench (SCHENCK). The fatigue cycles were performed according to the parameters given in Fig. 3. The plots of the electromechanical impedance measured after every cycling group are approximately identical (also at enhanced resolution). This means that the sensor connection shows essentially the same properties after and before the fatigue experiment. Similar tests on an aluminium helicopter tail boom (Mil 8) and slat tracks (Airbus A320) showed that the sensor connections and similar loads are stable far beyond 100.000 cycles (accompanying papers). In the present cases, only the Loctite Hysol EA 9309 3NA fulfilled our requirements concerning fatigue resistance.

3.3 Behaviour under thermal stress

The shielding against thermal stress is also difficult to achieve because it would require active heating or cooling of the sensor system and also passive isolation material is not sufficient considering the average flight duration. Here, material parameters must be selected that mechanical mismatch due to different thermal expansion is

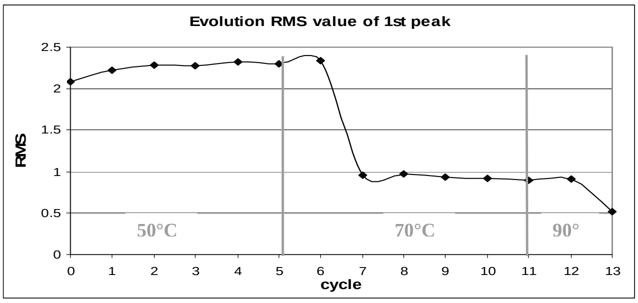

Fig. 4. RMS value of the waveforms under thermal stress. The connection failed when the temperature came into the range of the glass transition temperature of the epoxy glue.

minimal. In our case, the temperature stability was tested in dedicated test-chambers (Fig. 4), and the connection started to fail when the temperature came into the range of the glass transition temperature of the epoxy adhesive.

3.4 Behaviour under chemical stress

Chemical stress in aircraft arises from the contact of material with certain substances such as salt mist (leading to maritime corrosion), losing liquid catering products (causes floorbeam corrosion) or hydraulic fluids. If appropriate coating material is available, the destructive influence can be reduced. However, damaging of the coating and subsequent material degradation can have severe effects. A typical example of the effect of chloride ions on a sensor connection is shown in Fig. 5. The bonding between an aluminium sheet and a PZT having metallic electrodes was established by M-Bond 200 (cyanoacrylate glue), and the unshielded connection was exposed to a salt mist chamber. The total degradation was accomplished within about 7 hours, and the connection was most probably destroyed by a shortcut due to ionised liquid drops creating a galvanic element between the electrodes and the sheet material.

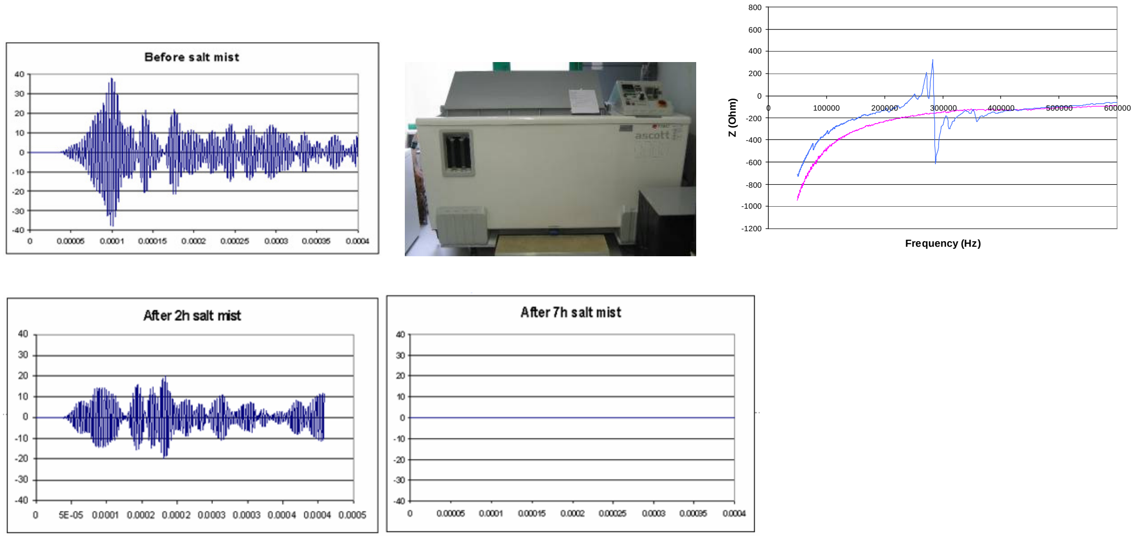

Fig. 5: Left side: Waveforms before, during and after treatment in the salt mist chamber. The sensor connection was physically detached due to electrochemical corrosion. – Right side: Impedance spectrum of the PZT patch before and after the salt mist test (2 h at 35°C with 5% NaCl, 7 h at 35°C with 5% NaCl)

4. Optical fibre sensors on composites

4.1 Set-up and adhesives selected

Optical fibre sensors working in the polarimetric set-up have a big potential in SHM (see e.g. [8, 9]). The SMARTape ® (SmarTec/Switzerland) optical fibre sensor used here (see Fig. 6) has a single mode fibre embedded in a thermoplastic PPS composite tape which has been reinforced with regular unidirectional glass fibre. This tape ensures a good protection of the brittle and very fragile optical fibre inside. The tape is 13 mm wide and 0.2 mm thick. It can withstand temperatures ranging from -50°C up to 300°C.

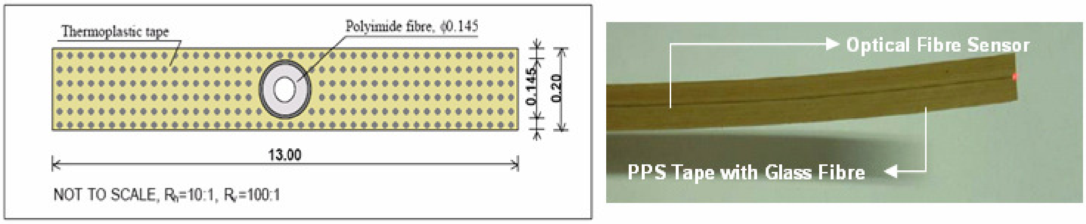

Fig. 6 SMARTape® thermoplastic optical fibre sensing tape

4.2 Behaviour under mechanical stress

The adhesion of the SMARTape optical fibre sensor was tested during mechanical and thermal loading. After a thorough search for possible adhesives, two of them were selected for further testing, UHU® "Schnell fest", a 2-component epoxy adhesive and Loctite Hysol® EA 9689, a film epoxy adhesive. The samples were equipped with two SMARTape® sensors (Fig. 7). The sensors were each attached with a different glue. The selection of the test conditions were guided by the requirements on a subsequent test performed on a helicopter tail boom. Typical in-service strains for this full scale object would be up to 0,4%. During our mechanical tests performed on the same kind of material (monolithic CFRP sheet in that specific case), the range of strain was between 0,5% and 1,0% (Table 1). This shows that our test conditions were more than relevant.

Load (kN)	**30**	**40**	**50**
Strain (%)	0.521	0.775	0.964
Δ L (mm)	0.833	1.239	1.543

Table 1 Overview of strain during mechanical (fatigue) loading.

The following test schedule was followed (Table 2):

° **Static loading** up to 20kN → unload			
° **Fatigue loading:**			
No exp.	F_{max}-F_{min} (kN)	Number cycles	Frequency
1	3 – 30kN	10000	5 Hz
2	3 – 30kN	20000	10 Hz
3	4 – 40kN	30000	10 Hz
4	3 – 30kN	30000	10 Hz
5	5 – 50kN	30000	10 Hz

Table 2 Loading schemes

After each cycling group, a C-scan was performed. The corresponding scans are shown in Fig. 7. It is obvious that the mechanical loading did not cause measurable additional disbonding of the sensors. The adhesives appear to be sufficient to ensure the adhesion of the sensors during the intended full-scale tests.

It can be seen that the Loctite Hysol® EA 9689 causes a higher attenuation of the ultrasonic signal, and this can be explained by the higher layer thickness inherent to that product. Lamb wave testing (i.e. use of ultrasonic guided waves) [9] also proved to be a problem, since the thicker layer gives enhanced acoustic attenuation. This resulted in very low amplitudes for the detected Lamb wave signals. Therefore, that glue was not considered in the subsequent measurements.

The lower sensor (Fig. 7) was glued with the UHU adhesive. It can be seen that there was an initial air bubble and another disbonded area present between the optical sensor and the sample. This can in principle be avoided with improved surface preparation before attaching the sensor, and by applying some pressure when the curing of the adhesive layer is performed. On the other hand, that initial disbondings even better illustrate the quality of the adhesive because their area did not increase during the heavy fatigue programme. Such artefacts would otherwise be an ideal trigger for accelerated disbonding.

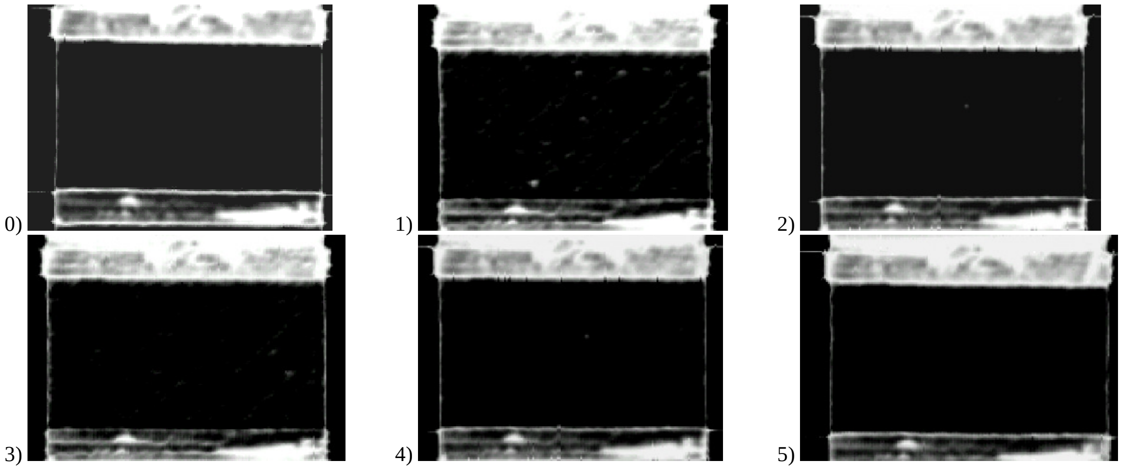

Fig. 7 C-scan showing SMARTape bond after mechanical loading: top sensor glued with HYSOL® EA9689, bottom sensor glued with UHU® after different fatigue parameters(see Table 2)

But further tests must ensure that the results are not falsified by close-fitting disbondings deluding an intact bonding analogous to the misleading signals obtained from closed cracks in metals. Moreover, C-scan is a good technique for the qualification of adhesives, but it is inappropriate for the self-testing of the sensor system when the aircraft is in service.

4.3 Behaviour under thermal stress

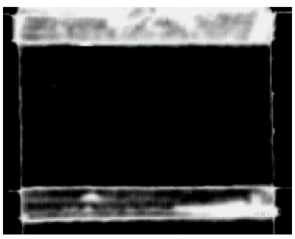

Fig. 8 C-scan after thermal loading

The same composite sample was also subjected to elevated temperatures. The plate was left in a temperature chamber for 1 hour at 90°C. Afterwards another C-scan was performed. The scan is shown in Fig. 8. If one compares this picture with the original scan (Fig. 7), it is clear that the bonded area has not changed. Although the temperature programme was much too short in the present example to be relevant in practice, the proof-of-concept show the principal usability of such tests.

Such as mentioned before, a specific problem arises from the in-service self-evaluation test of optical fibre sensors. An analogues technique to the electromechanical impedance is not available. On the other hand, optical fibre sensors follow the strains forced by the structure make a failure less probable compared to connection of piezoceramics and metal where the mismatch between elastic a brittle material is much more challenging. Moreover, there remains the option of using advanced signal transmission tests.

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