Structural Health Monitoring and damage detection of the helicopter main rotor blades with the structure integrated sensors

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Abstract:

Polish Military Fleet of Helicopters is mainly based on Russian made helicopters such as: Mi-2, Mi-8, Mi-17, Mi-14, Mi-24. This paper presents approach for structural health monitoring and damage detection in the main rotor blades of such helicopters. In the blade structure several failure modes may occur which affect structural integrity performance. These failure modes are critical from the flight safety point of view and are mainly fatigue cracks and corrosion. In order to assure safety NDT inspections are delivered. For such structures, however, NDT inspections are very time consuming and for some locations, results from inspections are difficult to asses. Therefore, study of the application of SHM techniques will be delivered for critical location monitoring with the use of:

- PZT (Piezoelectric Transducers) and guided waves for damage detection;
- FBG (Fiber Bragg Grating) sensors and stress/damage detection monitoring;
- CVM™ (Comparative Vacuum Monitoring) for local crack development monitoring;
- Resistance Sensors.

Based on specimens made from helicopter blades, a process of possibility of damage assessment will be presented as well as damage growth monitoring. Authors will deliver diversity of SHM techniques as well as elaborated techniques for signal analysis. The simulation results will be presented and the validation experiment will be delivered. Moreover, correlation of recorded signals with NDT used for in service maintenance will be presented to compare reliability of received data.

This work is the first step for the SHM implementation for the structural integrity monitoring of the critical components used in aerospace.

Keywords: SHM, guided waves, structural integrity, NDT

Introduction

In this paper approach for the Structural Health Monitoring for the helicopter Main Rotor Blades (MRB) has been considered. Most of the blades used in the Armed Forces are metal with the multisection structure. Differences are connected with the size, spar manufacturer and the number of blades in the rotor as well with the different values of service life as expressed in hours - HSL (Hour Service Life) and time - CSL (Calendar Service Life). One of the important issues regarding the maintenance of the metal MRB is the crack growth in the spar structure of the blade [1]. Detailed analysis of the failure modes allowed for determination of so called “hot spots” i.e. spar areas where the cracks occur most often. Another issue is the corrosion occurrence which may affect structural durability of such blades [2]. In the ITWL the project was conducted which aim was to develop the modern NDE techniques for CSL extension of the helicopter main rotor blades [3]. The first step of that work was to determine damages which could be detected and which happen during service life of MRB of helicopters used in Polish Armed Forces. These damages could be described as follows:

- Disbonds (skin to honeycomb, skin to spar);
- Cracks (in the spar);
- Corrosion (metal MRB);
- Water ingress (honeycomb cells).

This paper has been peer reviewed

The use of NDT gives information about structure integrity assessment. But these techniques have got also several limitations such as: time required for the inspection, difficulties connected with signal interpretation [3]. For that reason the use of SHM may be solution which enables monitoring of so called “hot spots” in the blade structure.

Structural Health Monitoring

For the monitoring of the blade damage the following SHM techniques were applied: PZT (piezoelectric sensors) and elastic waves propagation, FBG and strain monitoring. Also tests with CVM™ sensors and electrical resistance gauges were applied (it will be more extensively discussed in the conference presentation).

The PZT sensors as well as FBG sensor may be expressed as the global monitoring approach. It means that use of such sensors does not require the information about exact location of the crack. For the techniques such as CVM™ and electrical resistance gauges sensor attachment is required in the crack location.

Elastic Waves propagation

Complexity of a blade structure causes that modelling of wave propagation in this type of structure is a challenging task. FFT-based Spectral Element Method proposed by Doyle [4] is efficient but it is not applicable for 3D geometry. Some of researchers try to use methods based on the Finite Element approach or the Finite Difference approach such as LISA [5]. These methods are more suitable for modelling of complex geometries. Unfortunately, both methods are inefficient and lead to errors corresponding to numerical dispersion. Only few commercial packages enable modelling of generation of elastic waves by piezoelectric transducer but they also are based on FEM. In order to overcome disadvantages mentioned above, research group at IFFM have already implemented more accurate and efficient spectral element method [6,7]. Recently developed spectral elements also take into account electromechanical coupling [8].

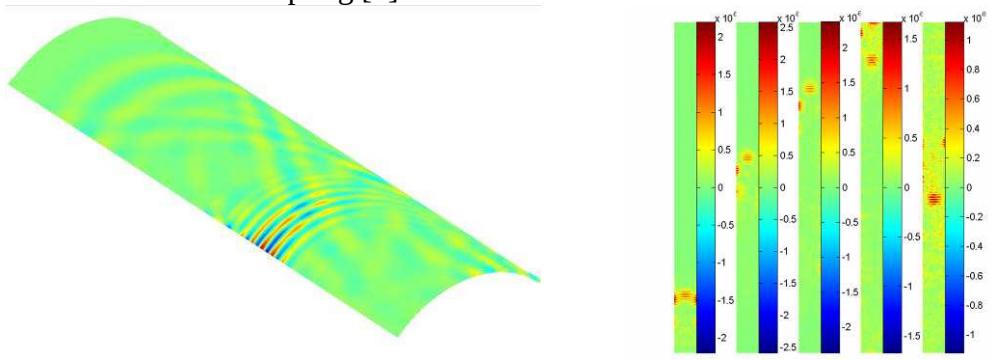


Fig.1 Elastic wave propagation modelling in shell-like structure (left picture) and in the helicopter main rotor blade (right) by the spectral element method

Fig.1 presents numerical simulation results obtained with the use of spectral method [9]. The use of numerical simulation enable determination of the reflections, transformations from the structural elements as well as propagation properties of the elastic waves. On the right picture propagation behaviour of the wave pockets in the spar structure (large length to width ratio). What is more issues connected with the modes separation and dispersion are shown.

Measured signals were processed with special signal processing algorithm. The surface of monitored specimen was covered with a uniform mesh of points $P_i=(x_i, y_i)$. Points separation was chosen to be dependent of the excitation signal:

$$d = A c_g \frac{N}{f_c} \tag{1}$$

where c_g – Lamb wave group velocity, N – number of sine cycles in excitation, f_c – excitation central frequency, A – ratio to be chosen. Distances between wave generating transducer to mesh point $|T_j\ P_i|$ and from this point to wave receiving transducer $|P_i\ R_k|$ were calculated and used to cut out a part of the propagating signal. Indexes i, j denote generating and receiving transducer, respectively. The cut out part, F_n, has a length of $L=s/c_g$ and is centred at instance:

$$t_{jk}^{i} = \frac{\left|T_j\ P_i\right| + \left|P_i\ R_k\right|}{c_g}. \tag{2}$$

Where s – distance between the mesh points.
This signal is discrete so the index takes values n=1,2,...,N, N depends on the length l. The signals are mapped into point P_i by summing signal power from all the T_j and R_k pairs:

$$M(P_i) = \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{n=1}^{N} F_n^2 . \tag{3}$$

This procedure is repeated for all point P_i in considered mesh. Such signal processing approach causes that the $M(P_i)$ lies on an ellipsis which loci are T_j and R_k.

In the conducted experiment A=0.1 was chosen. It gave a good balance between computational speed and resolution of the mapping. Results are depicted in Figure 2. Obtained results were normalised to the maximum value. Colour scale is from blue – minimum to red – maximum.

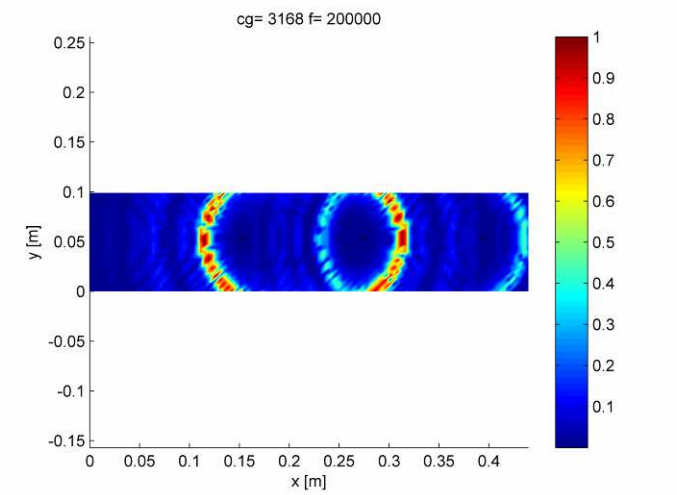
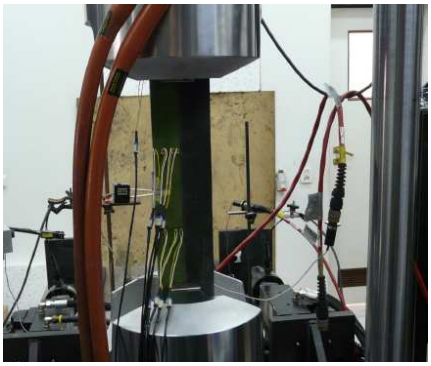


Fig.2 Damage detection result; black dots indicate the transducers positions

The first investigations gave interesting results. Numerical simulations were confirmed with the collected signals. Numerical techniques were developed for the signal assessment. Further investigations took into account damage detection and crack growth assessment. For that purpose the fatigue tests on the developed specimens have been made. Special sensor layout enabling *baseline free* assessment of the signal was designed. Moreover the multi-channel and multi-frequency approach was applied.



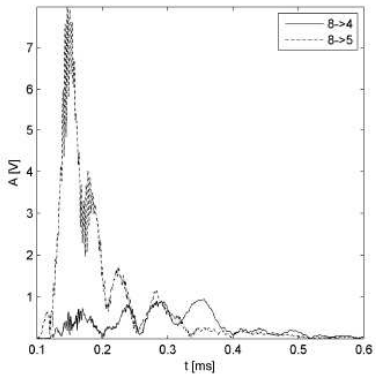


Fig.3 Specimen with array of the sensors and collected signals.

The number of specimens made from diversity types of blade was delivered. For measured signal the analysis techniques were elaborated. Signal analysis techniques may indicate the damage presence and damage growth with the use of so called damage index.

Measured signal (Fig.3) is filtered with the use of interactive filter (based on dedicated software created in ITWL). The algorithms are based on the FFT transform. For the purpose of further analysis the envelope of the signal is calculated in accordance with the following equation:

$$H[x(t)] = -\frac{1}{\pi} \int_{-\infty}^{\infty} \frac{x(r)}{t-r} dr \tag{4}$$

The magnitude of the analytical signal computed using the Hilbert Transform in equation (4) may be used for the determination of the damage index called “energy of the signal”:

$$E_{Di} = \int_0^t \sqrt{x(t)^2 + H[x(t)]^2}\, dt \tag{5}$$

The two signals are from the waves propagating in the damage free area (8->4) and in the crack location (8->5). The calculation of energy gives the clear indication of the damage and no damage state [9].

FBG for damage detection and strain monitoring

A typical structural health monitoring system is composed of a network of sensors that measure the parameters relevant to the state of the structure and its environment. One of the most important information is strain/stress distribution in the structure. Conventional sensors like electrical strain gauges are able to measure these parameters. But fiber optic sensors can give us improved quality of the measurements (especially in long term monitoring), better reliability and easier installation and maintenance. Even though fiber optic sensors are apparently expensive for widespread use in health monitoring, they are better approaches for applications where reliability in challenging environments is essential. Fiber Bragg Grating (FBG) optic sensor is one of the most promising in authors’ opinion.

New types of sensors and data acquisition systems have appeared, allowing a more reliable and economic instrumentation. Fiber–optic sensors are one of the most prominent technologies that have successfully migrated from the laboratory to the field [10]. The main benefits of fiber optic (in particular FBG sensors) have been

found in their long–term stability and reliability as well as in their insensitivity to the external perturbations like electromagnetic fields. These techniques have significant advantages in comparison to more conventional sensors, especially for structural health monitoring [11].

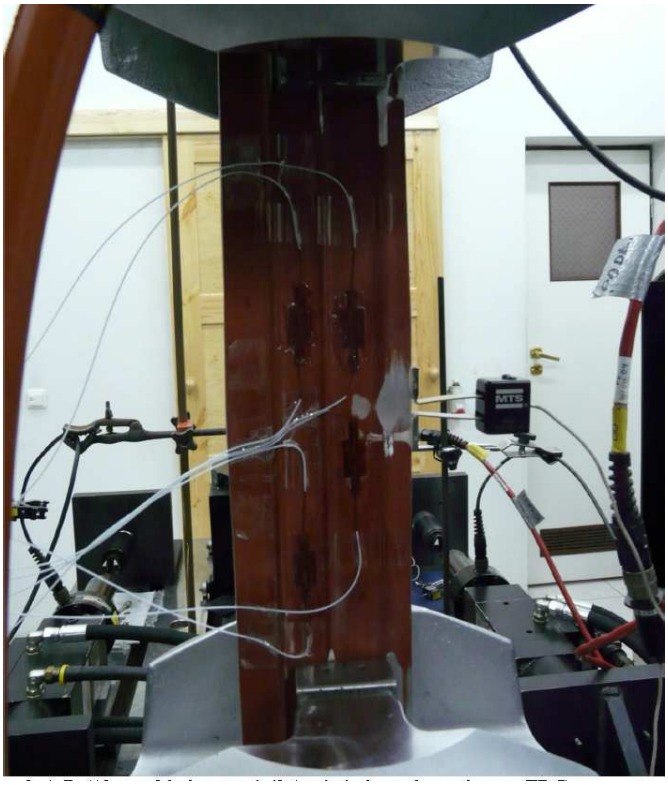


Fig.4 Specimen with FBG sensors.

Figure 4 presents the approach for the measurements with the FBG sensors installed on the specimen.
The layout of the sensors was designed to evaluate the numerical crack propagation FEM model and to quantify the damage presence and damage development during the fatigue test.

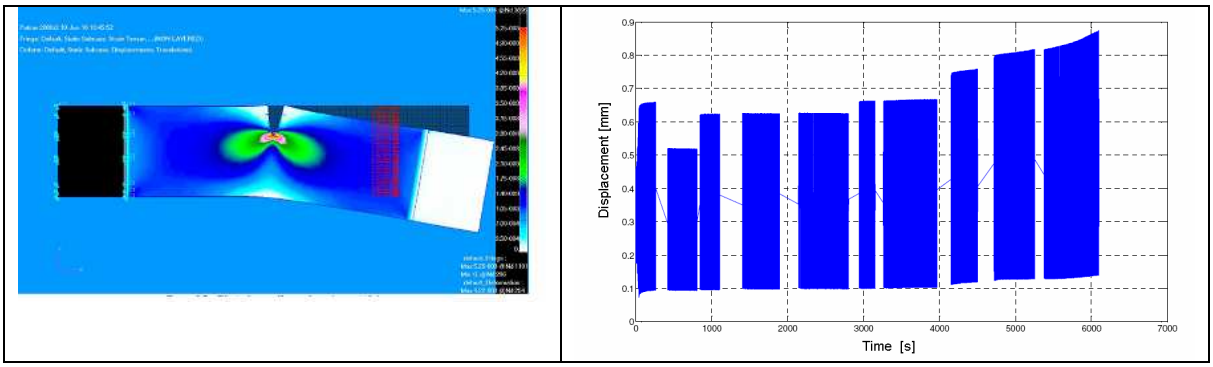


Fig.5 Specimen with FBG sensors and spectrum results of collected data.

Figure 5 presents the results of the numerical FEM simulation and displacement measured during the fatigue tests. The strong results correlation between the model and results obtained during the measurement were received. The displacement connected with the crack propagation was observed and measured with the use of

FBG sensors and similar results were obtained during the FEM simulations. The data collected during the measurements shows similarities to PZT sensors possibility of the damage presence and damage growth monitoring. There has to mentioned that there is a number of advantages and disadvantages of using FBG techniques (taking into consideration: implementation, durability of the sensor, sensitivity to damage presence and economical issues). There has to be discussed separately.

CVM™ and Resistance gauges

The application of the CVM™ and resistance sensors were delivered during the fatigue test. In the location with the stress concentrations (introduced mechanically notches) the above mentioned sensors were applied. The main goal was to asses sensibility of applied sensors for the crack development.

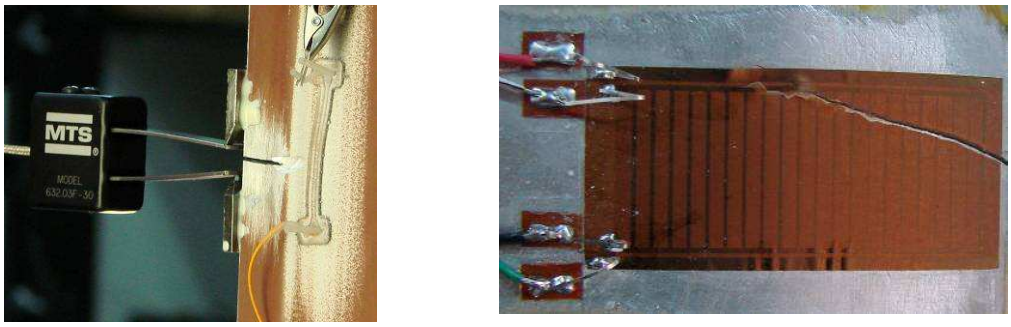
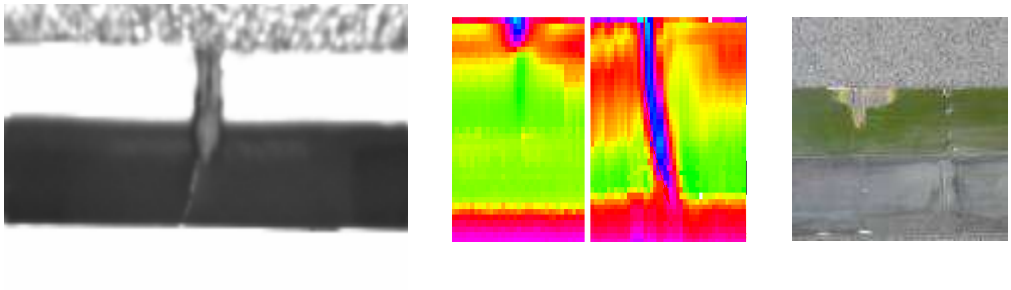


Fig.6 Specimen with CVM sensor and resistance gauge.

The number of sensors and locations was inspected. Depending on the type of the CVM™ sensor there is possibility to asses the size of the crack located under the sensor (as well for the resistance gauge). For the CVM™ sensor sensitivity for the crack closure has shown to be important issue. For that purpose measurement in the load state was necessary. That phenomena is not applicable for the resistance gauge. One of the disadvantages of such approach is the necessity of the sensor placement in the crack location. However, experience gained during the test will be used in other aerospace and similar applications.

Conclusions

All the results and data collected during the tests were correlated with the NDT techniques normally applied to the structural integrity assessment of the blades.



Crack lenght: **IT: 9,6 mm** **ET: 9,1 mm** **Visual: 10mm**

Fig.7 NDT results.

For the NDT verification the following techniques were applied:

- Infrared Thermography – IT;
- Eddy Current – ET;
- Visual (slide calipera assisted).

The data assessed with the use of NDT shows good correlation with the use of SHM (especially PZT and FBG). The further tests will be conducted on larger scale specimens. This work was done as the effort to characterize possibility of SHM application in the Main Rotor Blade of military helicopters. Especially introduction of such activities in the CSL extension will be valuable.

Different NDE techniques were used to determine possibility of such failure modes detection as:

- fatigue cracks;
- corrosion;
- disbonds and skin separation;
- water ingress (not delivered in the paper)

At present stage, possibility of inspection of the fatigue cracks with the integrated sensors is being under consideration. For that purpose different SHM techniques are involved such as: PZT, FBG, CVM™ and electrical resistance sensors. Tests are still in progress but the very first results are promising.

The following conclusions may be highlighted:

- There is knowledge about potential hot spots and most critical failure modes;
- The most promising taking into the consideration: effectiveness, economical factors, applicability, local vs. global area of monitoring is the elastic wave generation;
- There is still work in progress in the area of:
  - Rear web crack detection;
  - Corrosion Monitoring;
  - Further software development, Phased Array application, Time Reversal;
  - Work in progress in the Damage Index for failure mode characterization and NDT size correlation.

References

1. Shaniavski A.”Scale levels for fatigue fracture mechanisms of in-service crack growth in longerons of helicopter rotor blades”, International Journal of Fracture, Volume 128, Number 1/July, 2004;
2. Dragan K., Klimaszewski S., “Multimode NDE for structural integrity monitoring of helicopter main rotor blades”, International Workshop on Structural Health Monitoring, Stanford University, 09.09.-11.09.2009 r;
3. Dragan K., „NDE activities connected with Service Life Extension of Main Rotor Blades of Helicopters”, 7th Australian Pacific Vertiflite Conference on Helicopter Technology, 9 - 12 March, 2009;
4. Doyle, J.F. “Wave Propagation in Structures,” Springer-Verlag, 1997.
5. Delsanto, P.P., Schechter R.S, and Mignogna R.B., 1997. “Connection machine simulation of ultrasonic wave propagation in materials III: The threedimensional case,” *Wave Motion*¸ 26:329–339.
6. P. Kudela, A. Zak, M. Krawczuk, and W. Ostachowicz, 2007. „Modelling of wave propagation in composite plates using the time domain spectral element metod,” *J. Sound Vib.*, 302:728745.

7. Ostachowicz W, Kudela P., 2009. Spectral Element Method for wave propagation modeling in 2D and 3D solids, Proc. of the 7th Int. Conf. on SHM, 2:2213-2221, Stanford, USA.
8. Kudela P., Ostachowicz W., 2009. "3D time-domain spectral elements for stress waves modelling," 7th Int. Conf. MPSVA, Cambridge, UK, *J. Physics: Conf. Series*, 181 paper no 012091.
9. K. Dragan, S.Klimaszewski, P. Kudela, P. Malinowski, T. Wandowski, "Health Monitoring of the helicopter main rotor blades with the structure integrated
sensors", EWSHM 2010, Sorrento, Italy, 29.06 – 02.07.2010;
10. Glisic B., Inaudi D., 2007, Fiber Optic Methods for Structural Health Monitoring, John Wiley & Sons, Hoboken, West Suessex.
11. Udd E., 2006, Fiber Optic Sensors: An Introduction for Engineers and Scientists, John Wiley & Sons, New Jersey.