Application of resistive ladder sensor for detection and quantification of fatigue cracks in aircraft structure

Artur Kurnyta

Air Force Institute of Technology, Warsaw, Poland

Abstract: The paper presents preliminary laboratory verification of resistive ladder sensor application. The sensor, which is akin to foil strain gage, can be used for detection and length quantification of fatigue cracks. Special measurement circuit for data acquisition was developed and test specimens were prepared. Afterwards, laboratory tests on fatigue-testing machine were elaborated to explore utility and reliability of proposed method for crack detection. After analysis of acquired data, some observation and conclusion were drawn, especially about electronic circuit. Modifications in measurement system were described and simulated in Micro-Cap – an electronic circuit analysis program. The paper is concluded with summary from laboratory tests and simulations.

Keywords: fatigue crack, crack detection, resistive ladder sensor, electronic circuit simulation, Micro-Cap

Throughout service, aircraft takes many hours of flight, during of which it is subjected to varying loads. Under the influence of those stresses, appearing periodically, undesirable and irreversible changes in structure may appear. As a consequence, cracks are formed, which reduce the structural strength, significantly affecting the integrity. For that reason, intensive researches are carried out around the world, to develop innovative, reliable methods for detection of cracks initiation and propagation.

1. Introduction

There are few approaches to monitor structural integrity of aircraft structure during service. One is off-line NDI (Non Destructive Inspection) testing, during periodical survey. Many innovative measurement methods are used, like VI (Visual Inspection), UI (Ultrasonic Inspection), ED (Eddy Current) or thermography [1, 2]. All of above have very high probability of detection fatigue degradation of aircraft structure, even in micro scale. However, NDI inspection is usually time-consuming and labour-absorbing.

For that reason, on-line and real-time inspection methods are recently taken under investigation. There are advanced studies about using strain gages, FBG (Fiber Bragg Grating), piezoelectric or MEMS sensors for this purpose. The paper presents an easy, real-time method for crack detection, using resistive ladder sensor.

1.1. Resistive ladder sensor

As a part of studies for a modern and real-time crack detection concept, preliminary verification of resistive ladder sensor were conducted. The sensor's structure and manufacturing process is similar to foil strain gauges. Differences in shape of the measuring grid can be noticed, which is designed as a parallel connection of thin, electrically conductive paths.

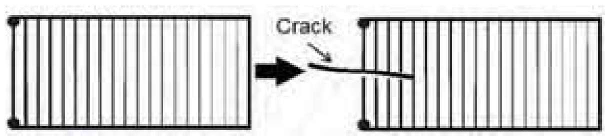

Fig. 1. Example of resistive ladder sensor
Rys. 1. Przykład rezystancyjnego czujnika drabinkowego

When crack is moving under the sensor, it is causing a local deformation, and gradually tearing the foil of the sensor. Concurrently with the foil, permanent open out of conductive path occurs. Electrical resistance measured between the sensor's two terminals changes, so on the output signal, in accordance to Ohm Law, which is described:

$$U = R \cdot I \tag{1}$$

where:
U – output voltage [V];
R– resistance [Ω];
I – current [A].

Method of integrating the sensor with a structure is identical as for regular foil strain gauges. In this way, by fitting such a sensitive element in a location suspected of surface cracks, and measuring its resistance, the possibility to detect and quantify fatigue fracture arises.

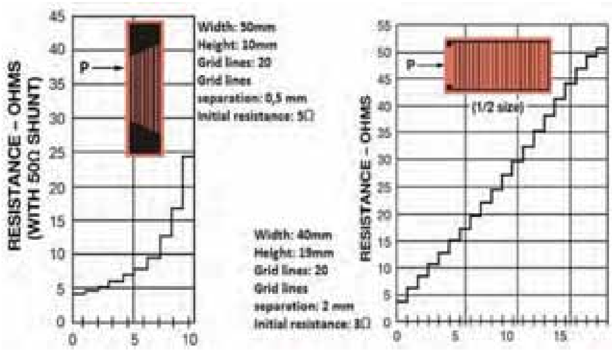

Fig. 2. Resistance characteristics of two types of sensor [4]
Rys. 2. Charakterystyki rezystancyjne dwóch typów czujnika [4]

Two types of sensor have been taken under investigation. First one has nonlinear characteristic, 20 grid lines with 0.5 mm separation. It guarantees good crack length quantification on narrow area.

The other type of the sensor has linear characteristic, 40 grid lines with 2 mm separation. Linear characteristic is achieved by different width of conductive paths.

1.2. Sensor's measurement system

To perform measurements with the resistive ladder sensors, it was essential to develop a special electronic circuit.

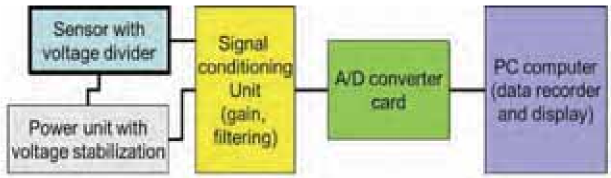

Fig. 3. Block diagram of measurement system components
Rys. 3. Schemat blokowy elementów systemu pomiarowego

The sensing element was placed in a voltage divider, between 100 Ω precision resistor and ground connection. In this way, the output voltage from the divider is on a satisfactory level, and the sensor is protected against high input currents. Laboratory DC power supply was used for voltage stabilization of +5 V. Signal conditioning unit and A/D converter card are combined together in National Instrument USB NI-6215 measurement card, with analog input channels ±10 V and 16-bit A/D converter.

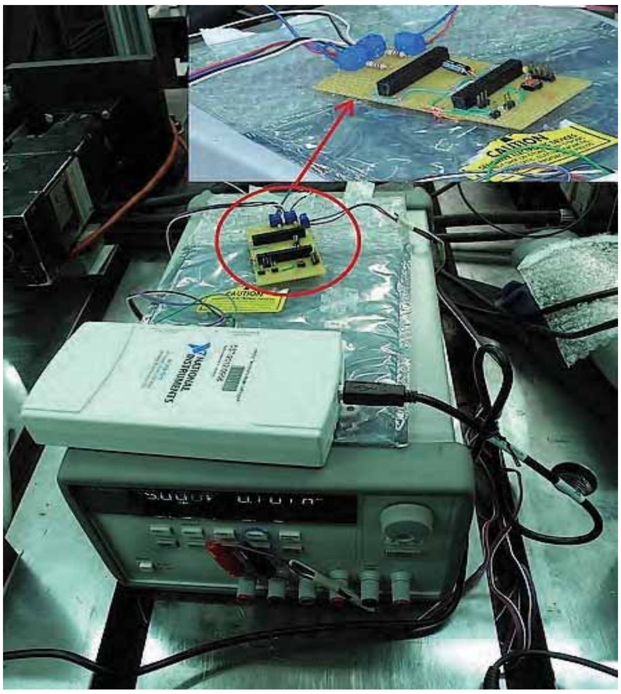

Fig. 4. Ready-to-run measurement system
Rys. 4. System pomiarowy przygotowany do pracy

The card was connected to PC computer via USB port with LabVIEW™ Signal Express software for data acquisition and display.

2. The course and results of tests

Preliminary tests were carried out on fatigue-testing machine, manufactured by MTS. The main goal of those studies was to provide some information about usability of resistive ladder sensor in crack detection, as well as to verify designed measurement system concept.

2.1. Flat, rectangular specimen

Firstly, studies were conducted on simple object, using flat, rectangular specimen. A little notch was made on one edge of the test object to provide a place of stress concentration. Used material was PA7 aluminium, specimen had dimensions of 160 x 50 x 2 mm (height x width x thickness). Applied axial load was in range 7÷12 kN, with a frequency of 10 Hz. Two, separate measurement channels acquired data from nonlinear and linear resistive ladder sensor, bonded on different sides of the specimen.

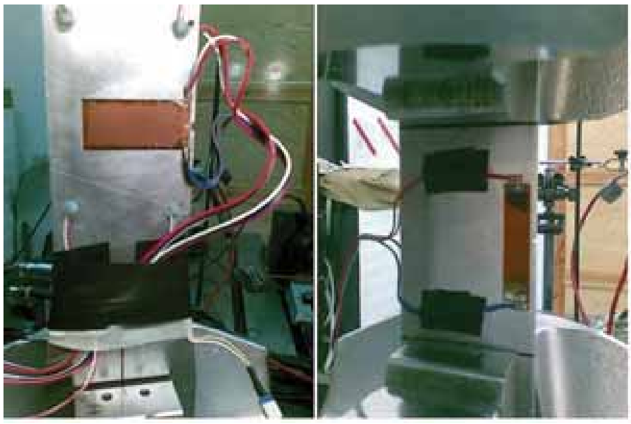

Fig. 5. Flat specimen view, front and back side
Rys. 5. Widok płaskiej próbki, strona przednia I tylna

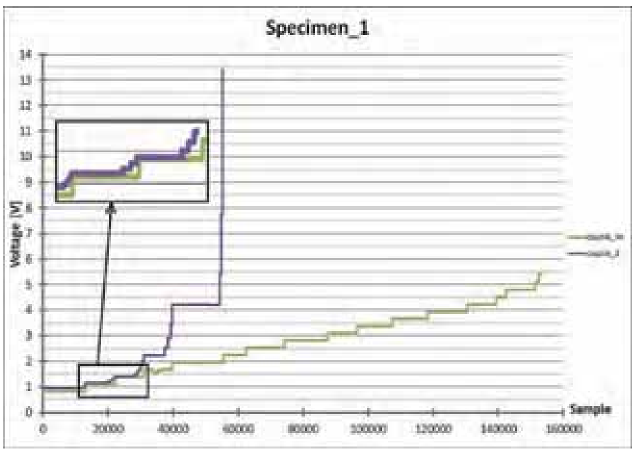

Fig. 6. Measurement data from nonlinear (purple line) and linear (green line) ladder sensor, specimen 1
Rys. 6. Dane pomiarowe z nieliniowego (linia purpurowa) i liniowego (linia zielona) czujnika drabinkowego, próbka 1

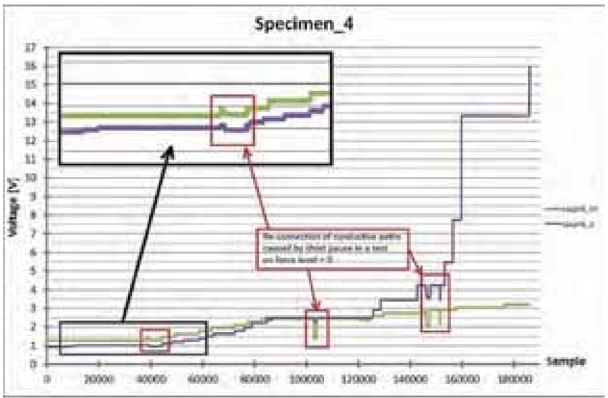

Fig. 7. Measurement data from nonlinear (purple line) and linear (green line) ladder sensor, specimen 4

Rys. 7. Dane pomiarowe z nieliniowego (linia purpurowa) i liniowego (linia zielona) czujnika drabinkowego, próbka 4

Acquired data from crack grow sensors are illustrated on graphs below, independently for two, identically prepared specimen.

Investigation confirmed a basic assumption, that resistive ladder sensors, permanently bonded to the structure, can successfully detect and quantify fatigue cracks. Fracture, moving under the sensor, was breaking conductive, parallel paths and in a consequence the output signal value from measurement system was changing. For a linear type sensor, equal steps of signal level can be noticed during the hole test. Nonlinear sensor's output signal is similar to this one from a datasheet, exponential type. That kind of characteristic cause a very little (about 10 mV) signal gradient at the beginning of fatigue crack development, which is almost 4-time less, then for each linear type sensor output value step. Regarding that observation, it may not be easy to notice and accurately determine a moment of initialization of the fatigue fracture. On the other hand, nonlinear ladder sensor provides better length monitoring of well-developed cracks, because of 0.5 mm, instead of 2 mm grid lines separation.

One disturbing observation was made, namely the reconnection of sensor's conductive paths, while the specimen was in unloaded state. After resumption of the test, the output signal came back to its previous level, although that fact could impose some limitations for conducting real-life measurement.

After tests on simple, small objects, and confirmation of basic assumptions of presented crack detection method, some investigation on real-life object was carried out.

2.2. Specimen from PZL-130 TCI aircraft

The real-life specimen was prepared, for further tests. A piece of wing from training aircraft PZL-130 TCI was chosen. There was a suspicion, that a fatigue crack can occur on the front longeron and adjacent skin area. If so, it could be critical to monitor that area from a crew safety point of view. A specimen was illustrated in fig. 8.

Two sensors of both sides of specimen were installed, one on the longeron, near a notch, and a second on the other side of specimen, on aircraft's skin. Unfortunately, for a day of writing this article, a fatigue crack had developed only on the skin, for that reason only half of data can be presented.

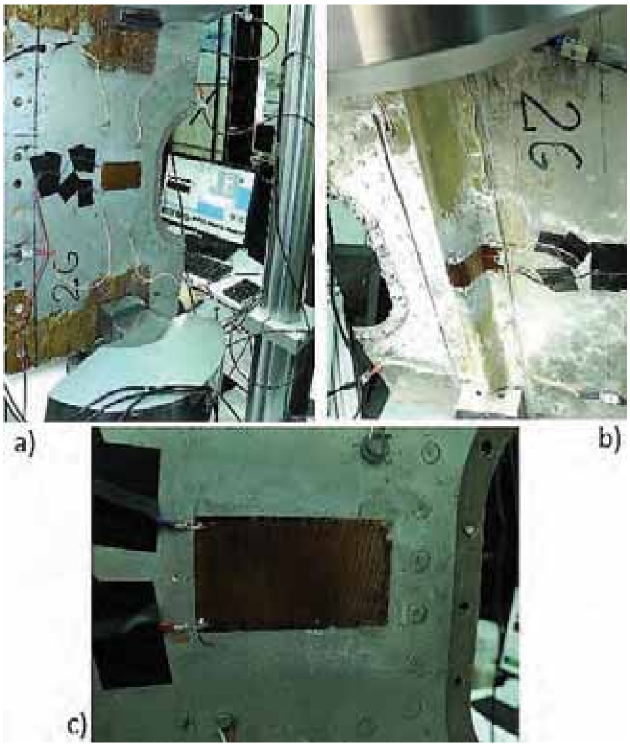

Fig. 8. Real-life specimen view, a)aircraft's skin side; b) longeron side; c) sensor permanently integrated with a structure

Rys. 8. Widok próbki rzeczywistej, a) strona poszycia; b) strona podłużnicy; c) czujnik trwale zintegrowany ze struktura

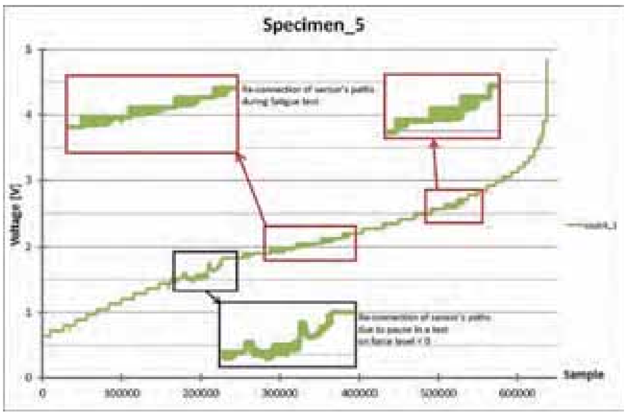

Fig. 9. Measurement data from ladder sensor, specimen 5

Rys. 9. Dane pomiarowe z nieliniowego czujnika drabinkowego, próbka 5

Test results are satisfactory, and similar to data from previous ones. Crack was simultaneously separating the specimen's material and sensor's foil with conductive paths. Some fine reconnection on the sensor was observed only one time during the pause in a test (black rectangle in fig. 9). Some minor reconnection was also noticed during the test was on (red rectangles in fig. 9), but a variations of output signal are almost unobservable, and only on few conductive paths.

3. Future measurement system upgrade analysis and simulation

Preliminary tests gave a lot of information, about utility of resistive ladder sensors, and designed measurement system. On the basis of that, some conclusions were made, how to improve the measurement system, especially its accuracy, resolution and reduce offset caused by voltage divider usage. Because of the fact, that future and complete system should be control not by a PC computer, but by an independent microprocessor system, an effective range of output signal shouldn't be larger than 0÷5 V. For that reason, electronic circuit analysis program Micro-Cap was used to develop and simulate necessary upgrades.

3.1. Sensor's neighborhood modification

Firstly, some modification in the neighborhood of sensor were made. Originally, sensor was a part of voltage divider which output signal is described as:

$$U_{out} = U_{in} \cdot \frac{R_{sensor}}{R + R_{sensor}} \quad (2)$$

where:

U_{out} – output voltage from the divider [V];
U_{in} – input voltage to the divider [V];
R – resistance of higher arm of the divider [Ω];
R_{sensor} – sensor resistance (lower arm of the divider [Ω].

In a measurement system, U_{in} was a power supply (+5 V) and R was represented by a precision resistor 100 Ω. This type of connection cause quite high initial offset for signal level. Assuming 3 Ω resistance for an initial value of a sensor, output voltage is about 150 mV, which is intensified by 5-time amplifier (750 mV).

An idea was put forward to use Wheatstone bridge, instead of voltage divider, which equation is:

$$U_A = U_B \cdot \left(\frac{R_1}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \right) \quad (3)$$

where:

U_A – output voltage [V];
U_B – input voltage [V];
R_1, R_2, R_3, R_4 – resistance of arms of the bridge[Ω].

If the bridge is balanced (resistance R_1÷R_4 have same value), the bridge output voltage is zero. So, if high resistance (500 Ω, 1 kΩ) will be used in a bridge, and a ladder sensor will be connected in series with R_1, an output voltage should be near zero in the initial state. That solution could successfully reduce offset, and as a result increase an effective measurement range.

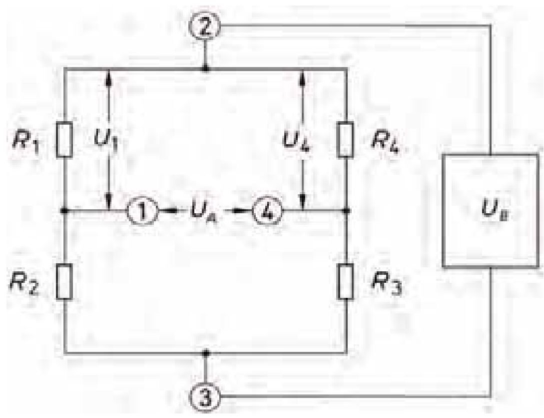

Fig. 10. Voltage-fed Wheatstone bridge [5]
Rys. 10. Zasilany napięciowo mostek Wheatstone'a [5]

3.2. Measurement system amplification

In connection with using Wheatstone bridge instead of voltage divider, some modification in signal conditioning unit need to be done as well. A resistance of the ladder sensor is low, comparing with resistors in a bridge. So, like for strain gages, high gain amplifier should be used to ensure good measurement resolution. It could be achieved by implementing differential amplifier, but eventually instrumental amplifier was chosen, due to better gain stability. What's more, an instrumentation amplifier has very high and equal input impedances, thus the element doesn't load the input signal source.

3.3. Simulation results

Very time-saving method of verification electronic circuit assumptions is simulation method, using SPICE language modeling. Micro-Cap is a software, which can be easily used for this purpose. It has very rich ready-to-use libraries of many, passive and active, electronic elements.

Upgraded measurement system, simulated in Micro-Cap software, is illustrated in Fig. 11.

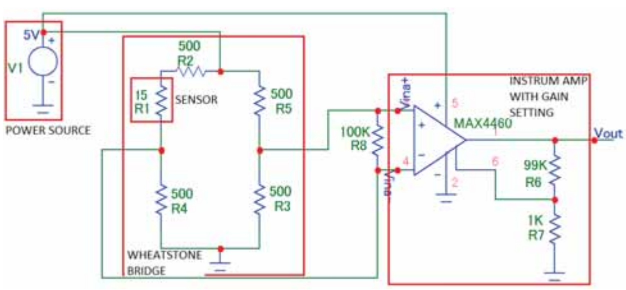

Fig. 11. Measurement system with applied modification
Rys. 11. System pomiarowy z modyfikacjami

There is +5 V voltage source, Wheatstone bridge with ladder sensor and instrumentation amplifier with gain setting resistors. Values of bridge resistors and the gain setting was defined by simulation results, to fulfil demanding of 0÷5 V output signal range.

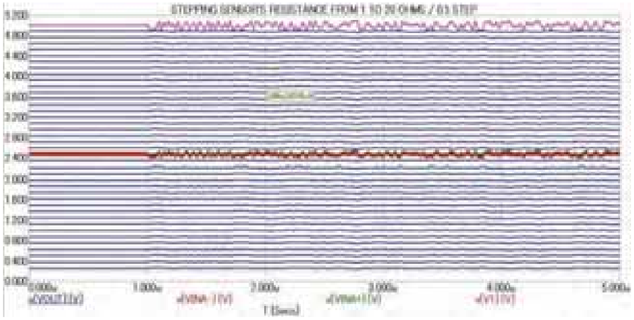

Fig. 12. Expected output signal range (blue curves)

Rys. 12. Spodziewany zakres sygnału wyjściowego (niebieskie linie)

Figure 12 illustrates the expected measurement range, when sensor's resistance changed from 1 to 20 Ω. Red and green curves represent voltage on amplifier inputs, and a pink curve is a value of voltage source. For better reflection of true conditions, voltage source was simulated as non-ideal source, by some noise addition.

Voltage source fluctuations are very undesirable in analog circuit, causing erroneous output value. Using Micro-Cap, it can be easily verified, how input source fluctuation can influence the output.

Two simulations were conducted with power source fluctuation. In the first one, noise amplitude was stepping from 0.1 V to 0.4 V. It can be seen in fig. 13 that even quite high voltage fluctuations don't cause meaningful output signal alteration.

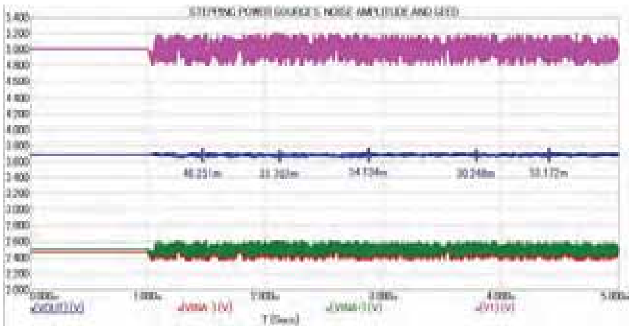

Fig. 13. Influence of power source's amplitude fluctuation on the output signal

Rys. 13. Wpływ fluktuacji amplitudy zasilania na sygnał wyjściowy

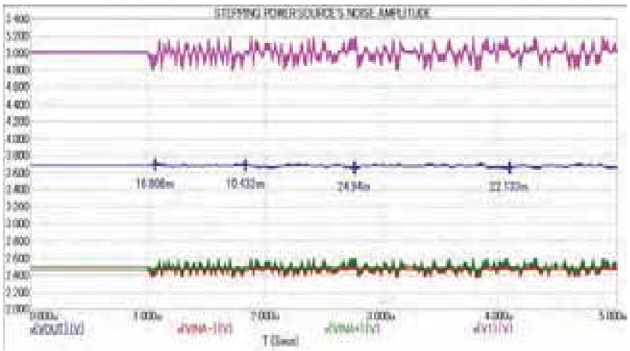

Fig. 14. Worst case: influence of power source's amplitude and noise frequency fluctuations on the output signal

Rys. 14. Najgorszy przypadek: wpływ fluktuacji amplitudy i częstotliwości szumu zasilania na sygnał wyjściowy

Second simulation represents the worst case, where power source amplitude and noise's frequency fluctuations were combined. In this case, output signal alter a bit more, but still less than change in ladder sensor's resistance for 0.2 Ω (typical resistance gradient for linear sensor is more than 0.5 Ω). That proves, that theoretically even in very noisy environment, a power source fluctuations has a little influence for the output value.

Summarizing, simulation model of measurement system performs all brief foredesigns about accuracy and offset, also provides very good resolution of output value for changing sensor's resistance during fatigue crack development. Now, PCB board should be designed and manufactured to proof adequacy of simulations.

4. Summary

The article presents the fatigue crack detection method based on resistive ladder sensor. To carry out laboratory tests, a measurement system was designed and specimens were prepared. Results were illustrated and described. Conclusions from laboratory tests help to improve measurement system, which was proven by simulation in electronic circuit analysis program. Next step is to develop the state-of-the-art application, which could be installed on an operating aircraft to increase safety level, decreasing time of maintenance.

References

1. Maley S., Plets J., Phan N. D., *US Navy Roadmap to Structural Health and Usage Monitoring – The Present and Future*, American Helicopter Society 63rd Annual Forum, Virginia Beach, VA.
2. Uhl T., „*Współczesne metody monitorowania i diagnozowania konstrukcji*", Wydział Inżynierii Mechanicznej i Robotyki Akademia Górniczo-Hutnicza, www.fundacjarozwojunauki.pl/res/Tom2/6_Uhl.pdf;
3. Speckmann H., Henrich R., „*Structural healh monitoring (SHM) – overview on technologies under development*", Proc. of the World Conference on NDT, Montreal – Canada, 2004. www.ndt.net/article/wcndt2004/pdf/aerospace/563_henrich.pdf.
4. [www.vishaypg.com/docs/11521] – Vishay Precision Group (20 grudnia 2012).
5. Kotowsky M., Dowding Ch., Fuller K., *Wireless sensor networks to monitor crack growth on bridges,* Conference on Developing a Research Agenda for Transportation Infrastructure Preservation and Renewal, November, 2009. ■

Zastosowanie rezystancyjnego czujnika drabinkowego do detekcji i określania długości pęknięć zmęczeniowych w konstrukcjach lotniczych

Streszczenie: W artykule przedstawiono wstępne badania laboratoryjne aplikacji rezystancyjnego czujnika drabinkowego. Czujnik, podobny do tensometru foliowego, może zostać użyty do wykrywania i określania długości pęknięć zmęczeniowych. Zaprojektowano specjalny układ pomiarowy do akwizycji danych, oraz przygotowano próbki. Następnie przeprowadzono badania na maszynie zmęczeniowej w celu poznania użyteczności i niezawodności zaproponowanej metody detekcji pęknięć. Po przeanalizowaniu danych pomiarowych wysunięto wnioski i spostrzeżenia, dotyczące zwłaszcza układu elektronicznego. Opisano proponowane modyfikacje układu oraz przedstawiono symulacje w programie Micro-Cap – programie do analizy układów elektronicznych. Artykuł podsumowano wnioskami z badan laboratoryjnych i symulacyjnych.

Słowa kluczowe: pęknięcia zmęczeniowe, detekcja pęknięć, rezystancyjny czujnik drabinkowy, symulacja układów elektronicznych, Micro-Cap

Artur Kurnyta, MSc Eng

Artur Kurnyta is a bachelor of Military University of Technology. He has been working in Air Force Institute of Technology in a Reliability and Safety Division since 2011. His areas of interests are: measurement systems, structural health monitoring, operational load monitoring, on-board data recorders, microprocessor system.

e-mail: artur.kurnyta@itwl.pl