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Designing opto-mechatronic systems for fatigue process monitoring

K e y w o r d s

Fatigue process, fatigue process monitoring, machine vision, opto-mechatronic system.

S ł o w a k l u c z o w e

Proces zmęczeniowy, monitorowanie procesu zmęczeniowego, maszynowe widzenie, system opto-mechatroniczny.

S u m m a r y

Opto-mechatronic systems enable one to conduct long-term fatigue tests where the observation of the surface of the specimen and the monitoring of cracking process are required. The rapid advancement of opto-mechatronic technologies and the functional interaction between opto-electronic and mechatronic components indicate that design and implementation processes of opto-mechatronic systems require specific methodology. The presented methodology describes and considers the interactions between components, particularly inside the vision module. The design process can be supported by simulation models, databases, decision matrices, and the method of conducting the implementation maturity assessment of innovative technological solutions.

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Introduction

Advanced research works in the field of fracture mechanics and fatigue fracture in structures under mechanical and thermal stresses are often connected with the long-term monitoring of fatigue crack propagation. Test results, obtained in this way, allow the assessment of the fatigue life of materials after the analysis of crack length related to stress intensity [2, 14].

The development of novel mechatronic, opto-electronic and computer technologies has enabled the creation of machine vision systems. At present, the term *opto-mechatronic system* is increasingly used to emphasise the integration of mechatronic and opto-electronic components in a system and the obtained synergistic effect of this combination [4]. Applying a vision system, a mechatronic positioning unit, and software for image analysis and measurement process control, it is possible to conduct the inspection and monitoring of fatigue fracture in real-time. Information from scientific and technical publications indicates that there are presently few solutions that resemble an experimental setup [5,10]. Examples of measurement apparatus dedicated for laboratory fatigue tests and offered by specialised manufacturers are the following systems that use digital image correlation methods (DIC) for the analysis of surface deformation under loads: ARAMIS GOM mbH [17], Vic-3D Correlated Solution [16], and Trilion Quality Systems [18]. These systems are stationary, equipped with a dual-camera vision module of fixed position and software for image analysing. An example of a system for strain analysing at the macro- and micro-scale is the Laser grating extensometer LES [8], which is the result of cooperation between Polish research teams. The main module of the LES system is the integrated measurement head equipped with opto-electronic and mechatronic units. Automated systems for fatigue crack monitoring are a separate group of innovative solutions [7, 8]. Their distinctive features are as follows: a mechatronic unit for crack monitoring, high measurement resolution achieved by the reduction of the observation window to the area of the crack tip, and software for image analysis and crack length measurement.

The unique character of opto-mechatronic systems for fatigue process monitoring causes is that a suitable design methodology is required, taking into consideration the high level of measurement and functional parameters, and adaptability to different environment conditions during testing. Some problems concerning the design methodology of the apparatus for fatigue monitoring and crack measurement can be analysed and discussed, based on a review of published methods and research results in the field of fracture mechanics. Essential aspects of the design methodology of opto-mechatronic systems are described in [4], where the following important features of the systems are presented: the interaction between components, the integrated structure, and the multi-functionality of the system. As pointed out by author in the monograph, opto-mechatronic systems are distinguished from other systems by the design philosophy seeking intelligent solutions where innovative technologies are applied. At present, in the designing of opto-mechatronic systems, novel methods, and software tools are used, including, concurrent engineering [1], databases [13], and decision matrices [3,15] for solution optimisation.

Monitoring method

The method for monitoring a fatigue crack is based on the inspection of the surface using a CCD camera and digital analysis of the acquired images. The objective of image analysis is to detect and identify deformation in a surface structure typical of cracks. The quality of images depends on the camera sensor model, the lens type, and the applied lighting method. The vision system is identified by the working distance, the view area, and optical resolution (Fig. 1). Optical resolution of the vision system is determined by sensor resolution and lens features.

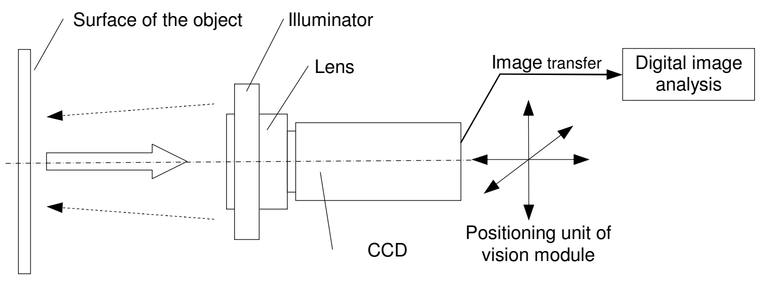

Fig. 1. General structure of the vision system
Rys. 1. Ogólna struktura układu wizyjnego

Among various methods of illuminating the sample surface, white light ring-illuminators are usually applied. Laser diodes emitting structured light are used for the illumination of the sample during surface inspection in macro-scale. The analysis of the light deformation on the surface makes the detection of cracks and crack length measurement easier. The detection of cracks is possible using advanced algorithms for image analysis. The most often used method is a digital image correlation method (DIC) based on the displacement analysis of characteristic points determined on the observed surface [2].

General structure of the opto-mechatronic system

The opto-mechatronic system for fatigue fracture monitoring has a modular structure that includes a vision module, a positioning module, electronic control units, and software (Fig. 2). In this system, the vision module is equipped with a single camera. It is the most often used solution. It is possible to apply multi-camera stereovision systems to create 3D images of the surface [6, 9]. The vision model is characterised by various parameters. For a CCD camera, essential parameters typically include trigger time t_{tr} and acquisition time t_a. The captured images $\{I\}$ are transferred from camera to computer. The lens parameters (zoom x_Z, focus x_F, iris X_I) can be set by the user manually, manually using a lens controller, or on the computer. For lighting system control, the following parameters are used: current supplying the light emitters I_c, trigger time t_{tr} and exposition time t_L. The triggering process of the lighting system and camera is coordinated. The operating position of the vision module is adjusted with a positioning module of n-degrees of freedom (n-DOF). In advanced opto-mechatronic systems, particularly for monitoring the non-stationary physical processes, electronically controlled positioning modules are used.

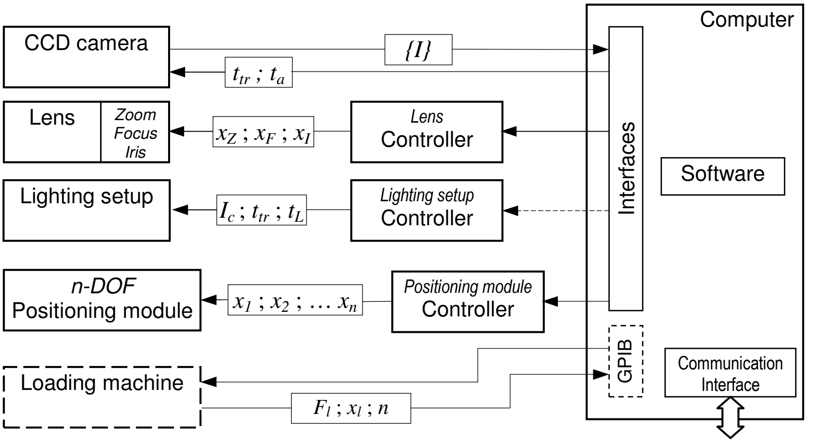

Fig. 2. Functional model of the opto-mechatronic system for fatigue tests
Rys. 2. Model funkcjonalny systemu optomechatronicznego wykorzystywanego w badaniach zmęczeniowych

In the presented system, there is an optical feedback between the camera and the mechatronic module, and information obtained from optical sensor is utilised for operating the motion of the vision module. This type of system can be used in laboratory fatigue tests conducted in a tensile testing machine, as well as in tests conducted on objects in an operational environment. In the first case, the communication between the computer and tensile testing machine (GPIB interface, for example) enables one to control the test execution and generate measurement data with reference to loads.

Novel opto-mechatronic systems that are used to conduct the long-term tests are more often equipped with a network connector, which allows web-based communication with a system. Remote access to a device (*telemonitoring*) enables the management of the system and on-line access to the database.

Design and implementation process of the opto-mechatronic system

Opto-mechatronic systems for fatigue process monitoring are examples of designs that incorporate innovative technologies. The main tasks of these systems include imaging of a surface in macro- and micro-scale, image processing, and analysis using high-speed algorithms, detection and identification of deformation in a surface structure, and fatigue crack tracking. In advanced fatigue tests, the monitoring possibility of fatigue crack processes with high measurement resolutions is an essential feature. In order to obtain these features, the innovative solutions, particularly concerning cameras and computing methods, should be applied. When designing opto-mechatronic systems, the interdisciplinary character of problem solving, the integration of components, and the flexibility of the system structure and functionality must be considered. Furthermore, due to the essential role of optical and opto-electronic components in a system, the team of designers should include specialists in new technologies at different stages of the development process.

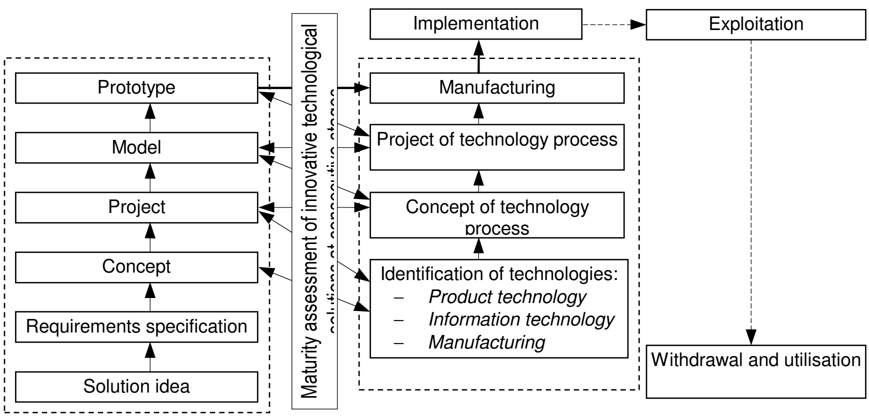

Fig. 3. Design and implementation process of the opto-mechatronic system using a systems engineering approach
Rys. 3. Proces projektowania i implementacji systemu mechatronicznego w ujęciu inżynierii systemów

Concept design of systems and implementation processes are important fields in systems engineering. Systems engineering employs the systems approach to the design and development of a system, which includes the interaction of the product with the environment during the operational life of the product [3, 4]. In this perspective, the design process, and the implementation of the opto-mechatronic system is presented in Fig. 3. Feedback connections between conceptual design and manufacturing technology design, and the implementation process indicate that concurrent engineering in system design is necessary. This means that the design and implementation methodology of opto-mechatronic systems should consider these relations at successive stages of the designing process.

Experience gained during the realisation of many research projects in the Institute for Sustainable Technologies – NIR show that the developed, original method of conducting the implementation maturity assessment of innovative technological solutions (SDW) became an important tool to support the design process [11].

When designing a highly advanced system, the designer should consider the present levels of technologies that will be needed to achieve the defined objectives. Examples of this case are opto-mechatronic systems for the monitoring of dynamic fatigue processes at micro-scale, where a high measurement resolution and high-speed acquisition and processing and the analysis of images are required. The designing process can be presented in a schematic diagram, where all important factors and relations between successive stages in the process are identified (Fig. 4). At the initial stage, the requirements for a system should be identified and specified, concerning the functions and technical parameters. In case of opto-mechatronic systems, this is the essential stage that determines the system architecture. A deep integration and interrelationship of components require the application of a concurrent engineering in designing of system's modules. For example, the structure of mechatronic positioning module directly influences the structure of the vision module, and the hardware and software architecture depends on the camera type. The design of the vision module is the process where basic components (cameras, lenses, optical filters, and illuminators) are selected from the offers available on the market. It is obvious that these products are limited in type, which causes problems for designers. For example, the appointed CCD camera imposes the type of communication with a computer. Therefore, the modelling of the structure of the camera-lens is often difficult because of a small number of acceptable alternative solutions. Designing the lighting setup is more flexible because of the possibility of developing one's own units specifically for the system, among other things.

The increase in the effectiveness of the designing process is possible by applying methods that use Multi-Criteria Decision Making (MCDM) [12]. Matrices that present alternative solutions of structures with regard to determined criteria enable one to identify the discrete set of acceptable solutions. In the first step, the several components regarding the determined criteria are identified, i.e. cameras, lenses, optical filters, etc. Matrices of components consist of rows with variants of products and columns with criteria. The set of criteria includes basic significant technical and functional parameters. The model matrices for determining the camera and lens at the design stage of vision module are presented in Fig. 5.

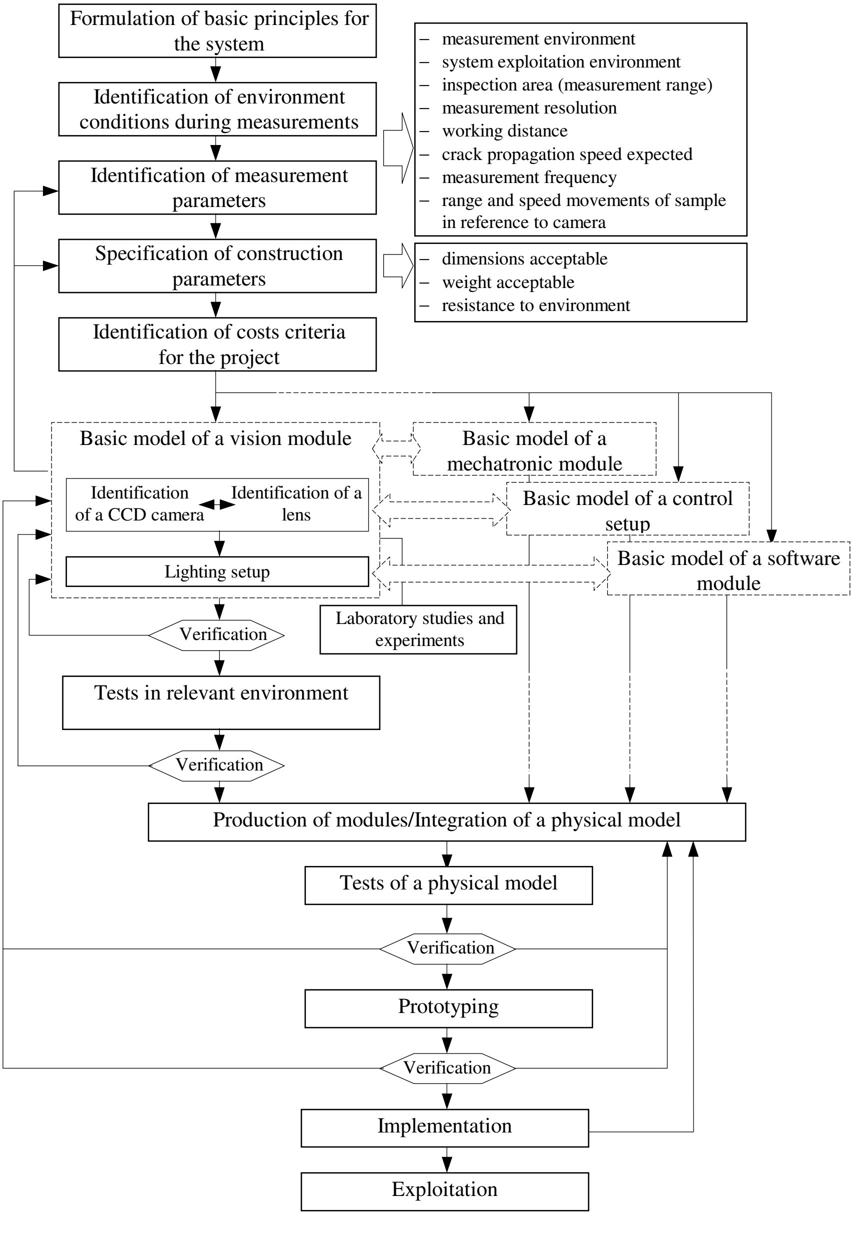

Fig. 4. Schematic diagram of the design procedure of the opto-mechatronic system (view detailed for a vision module)

Rys. 4. Schemat procedury projektowania systemu optomechatronicznego (szczegółowa prezentacja dotycząca modułu wizyjnego)

The <Cameras> and <Lenses> matrices are normalised, and each element of a matrix represents the value of each alternative with respect to each specified criterion. Components that fulfil requirements were identified by the analysis of matrices. The set of selected components was used to build the <Structure> matrix that returns a short overview of the best combinations of the camera with the lens. Then, the analysis of this matrix enables one to identify acceptable solutions. The final selection is executed taking into account the analysis of solutions, as well as the expert assessment. The method is relatively simple allowing a fast analysis and decision outcome.

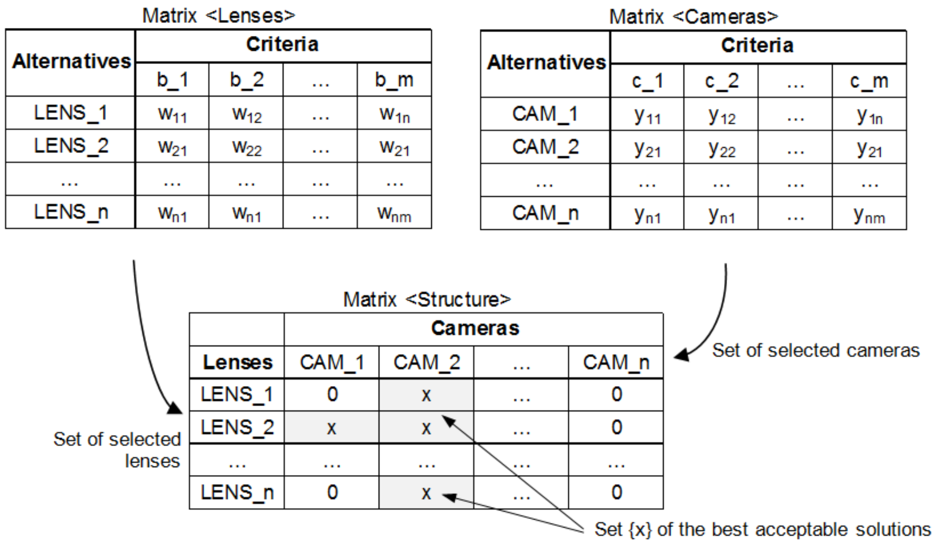

Fig. 5. Example that presents the application of matrices for the design process of a vision module
Rys. 5. Przykład wykorzystania macierzy w procesie projektowania modułu wizyjnego

Considering that concurrent design is used in design methodology, it is desired and appropriate to apply the multi-criteria decision analysis, where relations and interactions between components in a system are identified. By the reason of the variety of cameras, lens and other components, the computer databases and expert systems are important tools that can significantly increase the effectiveness of designing the opto-mechatronic systems.

Conclusions and summary

Design methodologies of opto-mechatronic systems applied at present do not sufficiently consider the unique character of innovative solutions that use opto-electronic, mechatronic and computing technologies for fatigue process monitoring. Opto-mechatronic systems are distinguished from other systems by extensive synergistic integration, and the structural and functional interrelationship of components. An example is the feedback loop between the vision module and mechatronic module that appears in the presented system for fatigue process monitoring.

The methodology presented in this paper shows and considers interactions between components, particularly inside the vision module. When designing the structure of vision module that includes camera, lens, and lighting setup, in most cases, the simulation and experimental modelling are necessary. The concurrent designing process of innovative system and manufacturing technology should be supported by the implementation of maturity assessment conducted at consecutive stages of solution development. Improvement of the design methodology of opto-mechatronic systems should take into consideration the application of the computer base of optical and mechatronic components, and also the multi-criteria analysis methods.

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References

[1] Bishop R.H. (Ed.): The Mechatronics Handbook. CRC Press, 2002.
[2] Boroński D.: Methods of strain and stress analysis in fatigue of materials and structures. Wydawnictwo Instytutu Technologii Eksploatacji – PIB, Radom, 2007 (in Polish).
[3] Cempel C.: Systems Theory and Systems Engineering – system thinking principles and applications. Wydawnictwo Instytutu Technologii Eksploatacji – PIB, Radom 2006 (in Polish).
[4] Cho H.: Optomechatronic: Fusion of Optical and Mechatronic Engineering. CRC Press, Taylor & Francis Group, 2006.
[5] Díaz F.V., Kaufmann G.H., Armas A.F., Galizzi G.E.: Optical measurement of the plastic zone size in a notched metal specimen subjected to low-cycle fatigue. Optics and Lasers in Engineering Volume: 35, Issue: 6, 2001, pp. 325–333.
[6] Garbacz P., Giesko T.: Concept of binocular stereo vision system for inspection of surfaces. Maintenance Problems 4/2010, s. 193–205.
[7] Giesko T., Boroński D., Zbrowski A., Czajka P.: Detection and measurement of fatigue cracks in solid rocket propellants. Maintenance Problems 3/2009, s. 75–84.
[8] Giesko T., Boroński D.: Automated machine vision systems for fatigue tests. Maintenance Problems 3/2003, s. 177–188 (in Polish).
[9] Hügli H., Mure-Dubois J.: 3D vision methods and selected experiences in micro and macro applications. Two and Three Dimensional Methods for Inspection and Metrology IV (proc. SPIE), vol. 6382, Issue 10, 2006, p. 209–216.
[10] Ju S. H., Liu S. H., Liu K. W.: Measurement of stress intensity factors by digital camera. International Journal of Solids and Structures Volume: 43, Issue: 5, 2006, pp. 1009–1022.

[11] Mazurkiewicz A., Karsznia W., Giesko T., Belina B.: Methodology of Technological Innovations Implementation Maturity Assessment. Maintenance Problems 1/2010, s. 5–20 (in Polish).
[12] Roy B.: Multicriteria methodology for decision aiding. Springer, 1996.
[13] Stark R., Beier G., Wöhler T., Figge A.: Cross-Domain Dependency Modelling – How to achieve consistent System Models with Tool Support. 7th European Systems Engineering Conference, EuSEC 2010, Stockholm, Sweden, 2010.
[14] Szala J., Boroński D.: Material fatigue analysis in diagnostics of machines and devices. Wydawnictwo Instytutu Technologii Eksploatacji – PIB, Radom, 2008 (in Polish).
[15] Van Beek T.J., Erden M.S., Tomiyama T.: Modular design of mechatronic systems with function modeling. Mechatronics 20 (2010), pp. 850–863.
[16] www.correlatedsolutions.com/
[17] www.gom.com
[18] www.trilion.com

Projektowanie systemów optomechatronicznych do monitorowania procesów destrukcji zmęczeniowej

S t r e s z c z e n i e

Prowadzenie długotrwałych badań zmęczeniowych wymagających obserwacji powierzchni próbki i śledzenia procesu rozwoju pęknięcia umożliwiają systemy optomechatroniczne. Wysokie zaawansowanie technologii optomechatronicznych i funkcjonalna interakcja pomiędzy komponentami optoelektronicznymi i mechatronicznymi powodują, że w procesie projektowania i implementacji systemów optomechatronicznych niezbędne jest zastosowanie odpowiedniej metodyki. Zaprezentowana w artykule metodyka wskazuje i uwzględnia interakcje pomiędzy komponentami, w szczególności w zakresie modułu wizyjnego. Proces projektowania może być wspomagany przez modelowanie, bazy danych, macierze decyzyjne i metodę oceny stopnia dojrzałości rozwiązania innowacyjnego.