A method of synthesis of small-sized high-speed optical measuring flaw detection systems

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Abstract A method for the synthesis of small-sized high-speed measuring flaw detection systems has been developed, with which it is possible to develop and create systems to solve said problem. For testing of this method, a prototype of the system was developed. Principles of developing of the prototype, its software operation and the results of its testing are provided in this article.

1. Introduction
During the operation of critical industrial equipment, the most loaded parts are subject to the appearance and growth of defects and mechanical damage. To ensure the reliability of industrial installations, regular inspections are required for timely detection of defects. It is important to obtain quantitative parameters for deciding on the possibility of further operation. During inspections, equipment is idle without performing useful work. Proper detection and quantification of wear and damage will allow performing maintenance in time, reducing the severity of the consequences and preventing serious damage to the plants, which will increase the reliability and durability of the equipment, reduce the time for servicing and increase the life of the most loaded parts of the equipment.

The authors have proposed a method for the synthesis of small-sized optical systems that can detect small defects on moving surfaces of equipment and obtain quantitative parameters about their shape [1]. The developed method made it possible to design a prototype of systems for analyzing the surface condition of critical equipment parts, including when they move when accessing through narrow technological holes.

In particular, tasks of inspecting the blades of steam and gas turbines of power plants and rotor blades of aircraft gas turbine engines were examined.

The prototype of the system developed in accordance with this synthesis method and the results of its tests are provided in this article.

2. Methods
The synthesis method for a small-sized high-speed measuring flaw detection system consists of the sequential solution of the following subtasks:
- synthesis of the lighting unit, including the calculation of the diffractive optical element;
- synthesis of an optical receiving system;
- synthesis of system software.

Each task has been solved giving an initial data and design features for creating the nodes of prototype of the system [1].

The prototype of measuring optical small-sized system has been created according to the said ideology. The system is mounted on a flexible delivery system, equipped with a laser illuminator, which forms a structured illumination of a known shape on the surface of the object. Prototype nodes are presented in figures 1–4.

The prototype of endoscopic system consists of:
- a miniature digital stereo system, forming a digital image of the object of study,
- a lighting unit,
- a laser illuminator,
- a mechanical articulation system;
- an articulation control panel;
- software for receiving, processing and displaying information.

Figure 1. Articulation control system joystic.

Figure 2. Articulation control system.
Figure 3. Laser pulses regulating system. Figure 4. System executive part.

The lighting unit consists of a semiconductor laser. The laser light is directed into the optical fiber. At the exit from the fiber of the laser light flux, a lens is located to impart necessary convergence to the flux; a Diffractive Optical Element (DOE) is located in the focal length of the lens. DOE has been synthesized before [1, 3]. The entire executive part of the system is removed in a flexible housing in the form of a tube. The control surface is inspected by a miniature optical stereo system, while a laser image of small spots with a known pattern is projected onto the surface. The image formed by the stereo system, including two small-sized cameras, is transmitted to the computer via the USB interface.

Using a digital image of an object and a laser image of laser spots projected onto it, computer software performs surface restoration and in case of a discontinuity, its shape is measured.

To measure the parameters of the discontinuity of the surface of the test object, software was developed that implements the work of the prototype flaw detection system. This software allows one to:
- calibrate an object with a known checkerboard shape — with white and black squares;
- receive an image from the optical system of the camera and record it on the computer's hard drive;
- restore the three-dimensional element of the surface of the object, observed from one angle;
- combine surface elements observed from different angles;
- automatically identify defective areas on the surface of the part;
- calculate the length and width of defects.

The results are displayed in a tabular form and saved to the hard drive.

The principle of the software is in performing the following sequences.

Calibration of cameras is carried out due to repeated shooting of the calibration template, key points can easily be distinguished in the image for which their relative positions in space are known. Next, systems of equations are compiled and solved (approximately), linking the coordinates of the projections, the camera matrix and the position of the points of the template in space. A depth map is constructed from a stereo pair of images.
For each point in one image, it searches for a pair of points in another image. By a pair of corresponding points a triangulation can be done and coordinates of their inverse image can be determined in three-dimensional space. Knowing the three-dimensional coordinates of the prototype, the depth is calculated as the distance to the plane of the camera.

The result is a point cloud that is characteristic when observed from the specific angle. When observing from different angles, complementary point clouds are obtained. The resulting point clouds overlap each other taking into account the redundancy of information in the intersection zones. As a result, a general three-dimensional model of the part is formed.

The superposition of two point clouds occurs using an iterative algorithm of the nearest points. The algorithm is applied in real time. The algorithm repeatedly applies the transformations (displacement, rotation) necessary to minimize the distance between points from two restored point clouds [2].

When implementing the prototype, the software was developed in order to realize the possibility of superimposing the elements of the object obtained from different angles to obtain complete information about the three-dimensional shape of the object.

The overlapping on the software has been realized using an iterative Closest Point (ICP) algorithm [4]. For its functioning, it is necessary to remove the surface from various angles with an overlap of 15–20%. These areas are used to compare the obtained surface fragments with the highest reliability. The algorithm works iteratively, the number of iterations to obtain a satisfactory result is 40–60.

Figure 5 shows an illustration of how the software works when combining information obtained from different angles

![Figure 5. Illustration of point clouds overlay in comparison with the real object.](image)

System tests were conducted in both static and dynamic modes. With a dynamic control the object was in rotation.

In a dynamic mode, laser lighting was adjusted by period and duty cycle to obtain optimal results. To obtain information on the minimum detectable deviation, objects in the form of turbine blades with artificially applied deviations of various sizes mounted on a rotating wheel were used. In dynamics, at a speed of 15 rpm, images were obtained. During subsequent processing, it was found that the minimum detectable deviation has dimensions in depth - 0.2 mm.

A series of experiments was carried out to determine the measurement error. For this in static mode, geometrical specimens were used with heights of 8.5 mm, 5 mm, 4 mm, 1 mm at working distances of 30 and 50 mm.

It was found that the measurement error of the characteristic sizes of objects does not exceed 6.6% [5].
3. Results
The prototype of the system and the software was tested on a mock-up of the bladed ring of a propulsion aircraft engine. A three-dimensional model and design documentation have been developed for a complete system of small-sized measuring flaw detection taking into account the corrections that appeared according to the test results.

As a result of the work carried out, a prototype of a high-speed measuring flaw detection system was developed and a program for image processing and analysis was developed with the aim of restoring a multi-angle three-dimensional image and detecting and quantifying parameterization of defects.

Such a system will allow controlling the shape of hard-to-reach parts for defects without dismantling and disassembling them. The application of the system allows reducing the examination time, and the risk of malfunctions during the operation of critical equipment in various sectors of the economy.

With the help of this system, it is possible to carry out both operational control and use it when extending the resource and assembling complex technological equipment.

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