Non-contact measurements of composite aircraft wing prototype under load

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Annotation. Measurements of general deformation of the wing box prototype of a medium-range passenger aircraft under load were carried out using non-contact videogrammetry (monogrammetry) method. The wing box was 9.8 m long and was made of polymer composite material. The tests were carried out on a special stand, where the variable loading of aircraft wing was simulated at ground and flight modes of a typical flight. The loading was carried out according to the program of tests up to destruction. As a result, the fields of distributed deflection strain were obtained for each loading step. It was shown that the maximum deflection in the end section immediately before failure reached 290 mm. The error in measuring the normal deviations of surface points did not exceed 0.8 mm.

Introduction
Investigation of strength properties of structural elements is one of the main types of tests in mechanical engineering and, in particular, in experimental aerodynamics [1-5]. This investigation requires measurements of deformations at a large number of points distributed over the sample surface. Currently, the most promising methods for measuring geometric parameters of displacement and deformation of objects are optical methods [6-11], in particular, methods of digital photogrammetry (videogrammetry). Such advantages of methods as: technological efficiency, non-contact, high information content (an image gives information about hundreds and thousands of points at the same time) and a wide measurement range (from 0.01 mm to tens of meters), - have provided them wide application in scientific research and measurement technology [12-15].

Videogrammetry method
Videogrammetry has become the next stage in the development of photogrammetry based on modern means of digital registration and numerical image processing [16-17]. The essence of the videogrammetry method consists in determining three coordinates $x, y, z$ of an object point in space using two coordinates $u, v$ of the response of this point on a digital image. In world practice, to resolve the uncertainty of reconstructing coordinates problem, the method of stereo photography (stereogrammetry) is commonly used, in such way two images of the surface of the investigated object are obtained using two cameras located at the distance commensurate with the distance to the object [18-20]. Combining the data obtained from two such images, one completes the working system of equations [21, 22].

However, in real experimental installations, it is not always possible to place two chambers at the desired points. The purposes of this experiment were application and adaptation of the videogrammetry (monogrammetry) method with one digital camera for measuring and visualizing the deformation fields of wing box prototype. To solve and close the working system, a priori information about an investigated object is used. [13, 23-24]. This method is reduced to the method of marker points, in which special markers are applied to the surface of an investigated object at desirable points. In doing so, marker points should be well optically distinguishable on a digital image. The missing information is found from known data about location of these markers in their original undeformed state.
The operating characteristic of measuring system, which provides a connection between spatial \((x, y, z)\) and digital \((u, v)\) coordinates, is written as a system of two nonlinear equations:

\[
\begin{align*}
    x &= (z - z_o) \left( \frac{M_{11}(u - u_0) + M_{12}(v - v_0) + M_{13}w_0}{M_{31}(u - u_0) + M_{32}(v - v_0) + M_{33}w_0} \right) + x_0 \\
y &= (z - z_o) \left( \frac{M_{21}(u - u_0) + M_{22}(v - v_0) + M_{23}w_0}{M_{31}(u - u_0) + M_{32}(v - v_0) + M_{33}w_0} \right) + y_0
\end{align*}
\]

where:

- \(u_0, v_0\) – coordinates of the center of the image, i.e. the cross point of object lens optic axis and digital camera matrix plane (in pixels);
- \(w_0\) – rear section of the receiver lens (in pixels);
- \(x_0, y_0, z_0\) – coordinates of the center of receiving lens (projection center) in the coordinate system of the model (in metric units);
- \(M_{ij}\) – elements of rotation matrix, directional cosines. Rotation matrix elements are functions of the orientation angles \(\alpha, \beta, \gamma\) of camera coordinates in the coordinate system of an object.

In photogrammetry terminology, the group of parameters \(P=\{x_0, y_0, z_0, \alpha, \beta, \gamma\}\) of operating characteristic that characterize the camera location in the measuring coordinate system is usually called photogrammetric parameters of external orientation., and the group of parameters \(Q=\{u_0, v_0, w_0, D\}\), related to the coordinate system of the camera and image, - parameters of interior orientation, \(D\) is an image geometric distortion parameter. The numerical values of performance parameters are obtained during calibration of the measuring system.

The coordinate system is chosen so that the displacements along the \(Oz\) axis are negligible or follow a predicted patterns. This assumption is used to close the system of equations, i.e. in this system (1) we will assume \(Z=\text{const}\) [11, 21-22].

The object of measurements

The object of measurements was a wing box prototype of medium-range passenger aircraft, 9.8 m long, made of polymer composite material. The \(Oxyz\) coordinate system was chosen so that the \(Oy\) axis is directed vertically upward, the \(Oz\) axis is directed along upper surface of the wing box along stringer, and the \(Ox\) axis of the right coordinate system is directed from the leading edge to the rear one (Figure 1). The VGM-system included: Vs-285 USB digital camera ("VIDEOSCAN"), a CCD-matrix of 1392 × 1040 pixels, a KOWA lens with a focal length of 16 mm, and digital image registration system based on a mobile computer with a package of specialized programs for image processing. The camera was located above the wing box, in a vertical plane passing between stringers 6 and 7. The distance from camera lens to wing box surface was about 5.2 m, and the angle between the optical axis and horizontal surface of the panel was about 30º. The distances from the center of camera lens to the coordinate system origin were 685, 5204, and 1390 mm along the \(Ox\), \(Oy\), and \(Oz\) axes, respectively. Illuminator was mounted on a tripod next to the camera. The images were registered on hard disk of laptop.

There are 35 measuring markers were installed on the upper surface of the wing box: 5 markers in each of 7 sections. The markers had circle form 10 mm diameter in the nearest section to 25 mm diameter in the far section and were made of reflective material. They were glued to the wing surface with vertical plastic pylons (Figure 2).
Preliminary calibration in order to determine the parameters of internal orientation of operating characteristic (1) of measuring system was carried out in laboratory conditions using a control device of clipboard type. Calibration in order to connect the VGM-channel coordinate system to the object coordinate system was performed for the wing box working image in stationary state, which was taken as initial conditionally undeformed state. Processing results of the calibration were processed using specialized programs in MathCAD computing environment. The result of two-stage calibration was a complete set of ten parameters of the operating characteristic (1) of measuring system, and the values of standard deviations along two coordinate axes $Ox$ and $Oy$.

Calibration of measuring system

When one measures large-sized objects, the VGM-system installation and operation of an experimental setup requires additional setting, which inevitably leads to change in the operating characteristic coefficients (1). In these cases, it is advisable to perform the calibration in two steps. The first step of two-step calibration is called the camera calibration. It is carried out in order to determine only photogrammetric parameters Q of the interior orientation. It is performed under maximum accuracy laboratory conditions using certified test fixture and verified auxiliary measuring instruments. After completing this stage, the setting state of receiving lens and camera is fixed and does not change during subsequent using of VGM-system. The processing of camera calibration results gives numerical values of all photogrammetric parameters of the operating characteristic, however, only the parameters of the interior orientation are significant. The external orientation parameters are ignored. In this experiment, to calibrate the camera, a high-resolution flat digital LCD monitor was used as a test object. A dense rectangular grid of local markers generated by a computer was displayed on its screen (Figure 3).

The second step of the two-step calibration is often referred to as the express calibration. It is performed on a experimental setup with a fully assembled and configured measuring system. Its purpose, in contrast to full calibration, is to determine only six photogrammetric parameters of the external orientation P of the operating characteristic with already known Q-parameters of the camera. This step can be performed using simplified and lightweight mobile control device and portable auxiliary measuring devices. Therefore, accuracy of express calibration is usually lower than accuracy of full calibration in a laboratory. Express calibration is recommended for mobile VGM-systems in difficult measurement conditions.

In this experiment, the second stage of calibration was carried out using a lightweight mobile rack type test-object (Figure 4), performed directly on the experimental setup with the investigated object. The test-object is an extended rectilinear metal plate with a number of measuring markers, with known coordinates, applied to its surface along the axis. A millimeter scale is applied along the edge of the rail.
The rack with attached plumb is vertically suspended on stand or tripod with knots for adjusting its position.

Control marks with known coordinates \((x^*, z^*)\) were applied on the surface of investigated object that way to more fully cover the VGM-system measurements area. The test-rack was suspended in turn so that the plumb was aimed to the next control mark. The vertical position of the test-rack was carried out on millimeter scale on it using a laser plane builder. A working image was recorded in each position.

**Tests of wing box prototype**

Tests of the wing box were carried out on a special stand, which simulated variable loading of aircraft wing. Test program provided for step loading with a step of 10% to 80% of design load; then continuous loading until wing box failure. At the initial state of the wing box, which is assumed to be unloaded state, the reference readings were made. Then, the images were recorded at each loading step in 5–10 frames with a frequency of about 3.8 frames per second. Example of a working image obtained during the tests is shown in Figure 5. At the final stage, the registration was carried out at the specified frequency continuously until destruction.

Image processing was performed using specialized software. The first stage of processing consisted in measuring of \(u, v\) marker coordinates on all images. At the second stage, \(x, y\) space coordinates of all
markers and their coordinate’s displacements from the initial undeformed (stationary) state were calculated. The estimates showed that at the maximum deflection of final section by 300 mm, the change of z-coordinate did not exceed 40 mm, that is, about 0.4% of caisson length. Therefore, the assumption of the constancy of z-coordinate can be considered justified.

Results
The bending deflection and the angle of torsion for each section were calculated by attraction (shift along two axes and rotation along the angle of attack) of the obtained x, y coordinates of markers for all sections at undeformed state to their coordinates in the current state using the least squares method [23]. At the same time, the minimum values of the root-mean-square discrepancies in two coordinates were determined, which served as an estimate of measurement error. As a result, bending and torsion deformation curves were constructed for each loading step. The results of the bending strain curve are shown in Figure 6. It can be seen from the graph that at the moment of failure, the maximum deflection in the end section reached approximately 290 mm.

![Figure 6. Bending deformation for each loading step](image)

In order to analyze the stress-strain state and deflections of the wing box, calculation of the box loading by a finite element method was carried out. Load application to design finite element model of the wing box was carried out by concentrated efforts at the locations of corresponding cradles. Comparison of calculated bending deflection with the measured before the caisson failure one (Figure 7) shows that bending deformation is generally corresponds to the expected, but there are noticeable discrepancies in the middle of the wing box. It was found that measurement error increases with increasing load and reaches a maximum of 0.73 mm in the third section (z = 6059 mm). The increase of standard deviation may caused by unaccounted deformations within sections themselves and the fact that the wing box turned out to be the most susceptible to such deformations in the vicinity of the third section.
Conclusion
On the example of an airplane wing box, the possibilities of using videogrammetry method with one camera (monogrammetry) for non-contact measurements of distributed normal deformation of large objects are shown. The method is also applicable to other structural elements in a strength experiment. Comparison of the measurement results with the calculation showed good convergence, which makes it possible to use this method for verifying calculation models under determining of stress-strain state of full-scale structural elements.

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