Investigation of deformation fields in aircraft panels by non-contact optical videogrammetry method

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Abstract An optical videogrammetry method using one digital camera for non-contact measurement of distributed normal deformation of the construction elements with a flat surface or having a small curvature is developed. Investigations of the surface buckling were performed at the local shell buckling of typical cylindrical fuselage panels of a passenger plane made of aluminum alloy and the general buckling of a full-scale flat panel of a perspective aircraft wing box made of a polymer composite material with a loading up to destruction. It was found that in both cases, the buckling deformation of the surface has two main modes with the opposite sign of normal deviations. In one of the tests two measuring systems are used simultaneously recording normal deviations of two opposite surfaces of panel skin. This made it possible to obtain a quantitative picture of skin thickening while its separation developing in the area of impact damage. Measurement error of normal deviations of the surface points is less than 0.1 mm.

Keywords: non-contact measurement, videogrammetry method, deformation fields

1 Introduction

Investigation of strength properties of construction elements is one of the main types of engineering tests and, in particular experimental aerodynamics tests. This investigation requires measurements of deformation components in a large number of points distributed over sample surface. Such measurements can be provided by non-contact optical videogrammetry method.

The essence of the method is following: one can find (determine) 3 spatial coordinates x,y,z of object point knowing only its 2 response coordinates u,v in the digital image. In the general formulation, the task of coordinates recovering is underdetermined, i.e. there are three unknowns and only two equations. In world practice, to solve the problem of ambiguous coordinates recovering a method of stereo photo is commonly used, which implies obtaining not only one image of the surface of object, but two ones from two cameras separated by a distance [1-2]. Combining data from such two images allows to enclose the operating system of equations.

However, in real experimental conditions it is not always possible to locate two cameras at the desired points. The aim of this work was to develop a videogrammetry method of non-contact measurement and visualization of strain fields of structural elements having a flat or slightly curved surface with applying only one digital camera. Enclosing of operating system of equations is achieved by using prior information about the test process (object) obtained during calibration of videogrammetry system.

Let's define a coordinate system in which OX axis is directed along the compression force and OY axis – along the average normal to surface. Thus the operating characteristics, i.e. system of equations for transformation image coordinates to the spatial coordinates of the object, can be represented as

$$X = (Z - Z_0)\frac{M_{11}(u-u_0)+M_{12}(v-v_0)+M_{13}w_0}{M_{31}(u-u_0)+M_{32}(v-v_0)+M_{33}w_0} + X_0;$$

$$Y = (Z - Z_0)\frac{M_{21}(u-u_0)+M_{22}(v-v_0)+M_{23}w_0}{M_{31}(u-u_0)+M_{32}(v-v_0)+M_{33}w_0} + Y_0 \qquad (1)$$

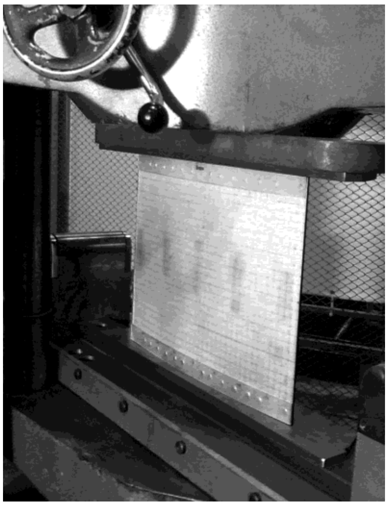
where:

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);

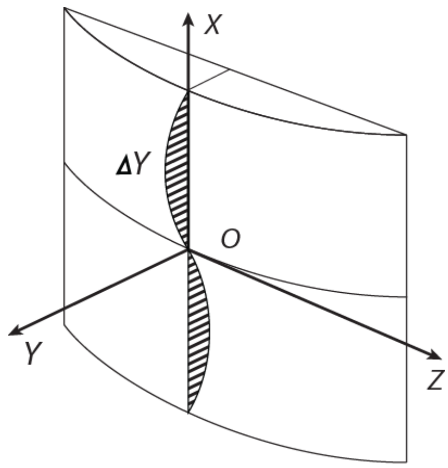
w_0 – rear section of the receiver lens (in pixels);
x_0, y_0, z_0 – coordinates of the center of receiving lens (projection center) in the coordinate system of the model (in metric units);
Mij – elements of rotation matrix, directional cosines. Rotation matrix elements are functions of the orientation angles α, β, γ of camera coordinates in the coordinate system of the object.
The numerical values of performance parameters u_0, v_0, w_0, X_0, Y_0, Z_0, α, β and γ are obtained during calibration of the measuring system [3].
In this problem, deviation of surface points due to buckling occurs along the direction of compressive force (OX-axis) and along the average normal to the surface (OY-axis). In the third orthogonal direction OZ deviation of points is negligible. This assumption is used to enclose the system of equations, i.e. in the system (1) we assume Z = const.
Efficiency of the method is demonstrated in studies of the surface buckling of typical cylindrical fuselage panels of a passenger plane made of aluminum alloy and the general buckling of a full-scale flat panel of a perspective aircraft wing box made of a polymer composite material with loading up to destruction.

2 Strength tests with use of videogrammetry method

In the first experiment, the test sample was a typical cylindrical panel (fragment of full-scale fuselage skin of passenger aircraft) made of aluminum alloy with dimensions along axes OX and OZ 290 × 380 mm respectively. Skin thickness was 1.2 mm, the radius of curvature about 1500 mm. Skin was strengthened with three pressed aluminum stringers oriented along the OX-axis of the cylindrical surface.
While preparation for testing a mesh with 37×23 black markers with diameter of 0.5 mm with the same step of 10 mm along the axes was applied on the outer surface of the panel. During the tests the panel was mounted vertically in the test machine and compressive load along the vertical OX-axis was applied to it (Figure 1). Digital camera with a resolution of 4095 × 4095 pixels and objective lens with focal length of 135 mm was used. The digital camera was located horizontally at the level of the middle of the panel. The distance between the objective lens and the middle of the panel was about 1400 mm, and the angle between optical axis and normal to the panel surface was about 30º. The results of calibration of the system configured showed that instrumental error (standard deviation) along the direction of surface normal is not more than 0.1 mm.



a



b

Fig. 1 Cylindrical panel in the test machine and coordinate sistem

Measurements were carried out with a compressive loading step of 200 kgf in the range of 200 to 4200 kgf. Basic frames are registered in initial state of the panel, the state under a load of 100 kg. Deformation was determined as the difference between current and initial normal Y coordinate of each marker on the surface. The measurement results showed characteristic wavy pattern of local loss of steadiness of skin appeared in two distinct modes of lateral deformation with opposite signs. It is shown that one mode with the deformation in positive direction (in the direction of radius increase) increases monotonously with loading growth, while the other shows a sharp increase of the deformation rate at loads in excess of 3600 kg. Figure 2 shows a three-dimensional graphical representation of the normal deformation field of the panel surface at maximum load of 4200 kg compression (σ = 43.16 MPa). The maximum deviation of the positive deformation mode was +1.26 mm, and -2.47 mm for negative one.

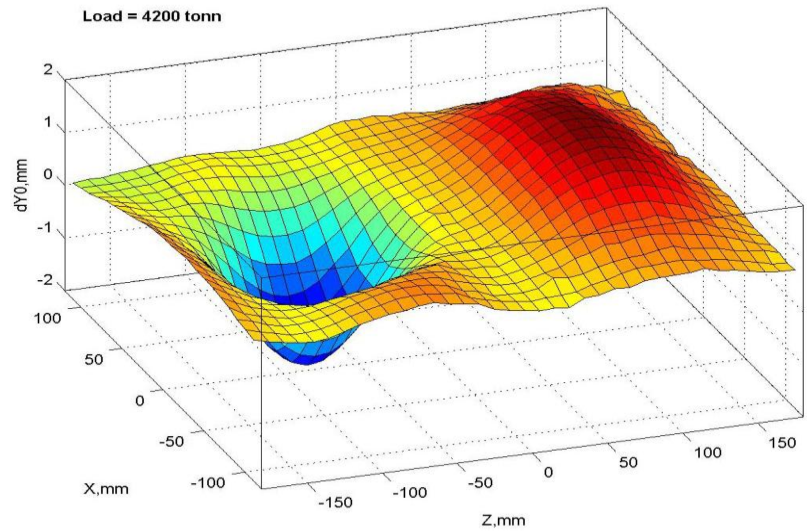


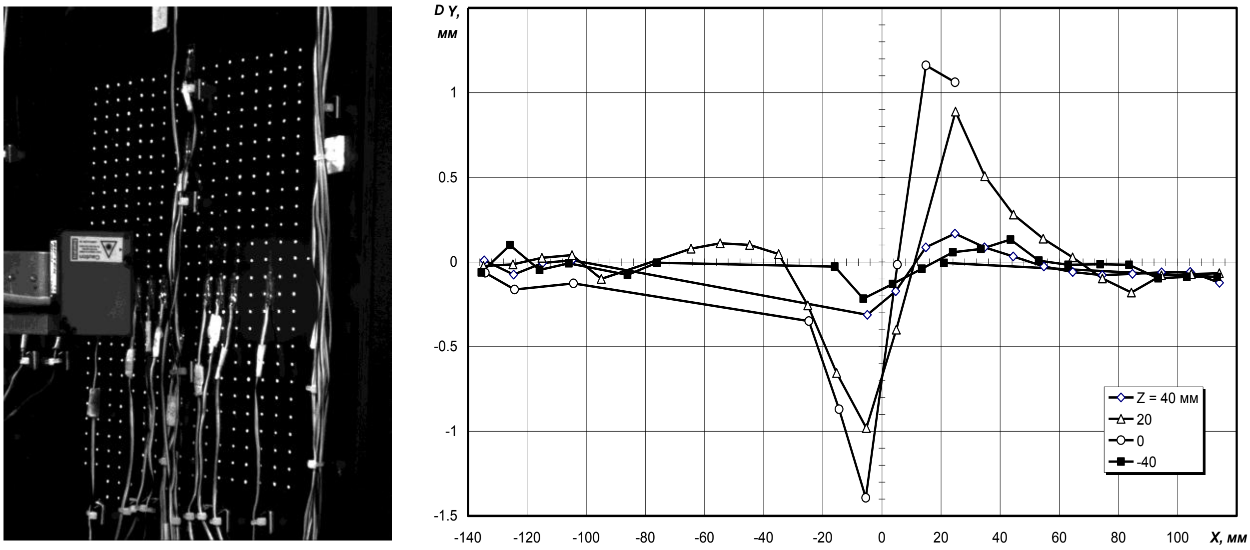
Fig. 2 Normal deformation field of the panel surface

In the second experiment, test object was a full-scale three-span flat panel of aircraft wing box made of polymer composite material with dimensions of 3800 × 62 × 360 mm and skin thickness of 6.5 mm, strengthened with five longitudinal stringers. Span under study was located between the second and the third stringers. It was subjected to local impact damage, which led, according to the results of ultrasonic inspection, to internal delamination of polymeric material in an area with a diameter of about 105 mm.

To implement the method of videogrammetry test the area of panel surface was marked with 26×17 mesh with size of markers 2×3 mm and steps of 10 and 20 mm along OX and OZ axes respectively. The panel was set vertically in the test machine, so that compressive load was applied along OX axis directed upwards. The digital camera was located horizontally at the level of impact. In these tests a digital camera with a resolution of 1392 × 1040 pixels and a lens with focal length of 50 mm was used. The distance between the objective lens and the point of impact was about 1860 mm and angle between an optical axes and normal to the panel surface was 67°.

From the beginning of loading the measuring system enabled a continuous recording of series of images with frequency of about 3.8 frames per second (260 ms period). Figure 3a shows a working image just before destruction of the panel.

Analysis of measurement results showed that the predominant surface buckling occurs in a radius of about 40 mm from the impact point. Buckling deformation of the surface in this area has also a wave-like form with an opposite sign of normal deviations of two basic modes. With increase of load up to destruction the amplitude of surface buckling monotonically increased. Diagram of normal deformation of the surface just before the destruction of the panel is shown in Figure 3b. The maximum wave amplitude recorded before the destruction reaches a value of more than 1.33 mm, which is about 20% of thickness of the skin.



a b

Fig. 3 Working image (a) and buckling deformation (b) in the area of impact just before destruction

At the third test to determine the characteristics of delamination of the panel it was proposed to measure deformation fields of two opposite sides of the panel simultaneously. The test object was a full-scale flat panel of aircraft wing box with dimensions of 400 × 400 mm and skin thickness of about 7 mm made of a polymer composite material, reinforced with three longitudinal stringers. Span under study was located between two neighbouring stringers. The skin there was subjected to local impact damage, which led, according to the results of ultrasonic inspection, to internal delamination of polymeric material in an area with a diameter of about 140 mm.

To implement the method of videogrammetry each surface of the panel was marked with two identical 19 × 27 meshes with marker diameter of 0.5 mm with the same step of 5 mm along the axes. The panel was set vertically in test machine, so that compressive load was applied along OZ axis. The measurement system contained two identical videogrammetry channels located from opposite sides of the panel. Each channel included a digital camera with a resolution of 1392 × 1040 with a receiving lens having a focal length F = 58 mm, and light source. Cameras were located symmetrically in the vertical plane passing through the impact point. The distance between the objective lens and the impact point was about 1000 mm and the angle between optical axis and normal to the surface of the panel was about 30º. The measurements were carried out in a step loading mode up to the failure of the panel. Basic images were taken at the initial state of the panel, at a load of 10 ton-forces. Subsequent measurements were carried out under a load of 20, 40, 60, 80, 100, 120, 140, 150 and 160 ton-forces. The destruction of the panel occurred at load of 163.5 ton-forces.

Deformation fields of outer and inner surfaces at the maximum load of 160 tf are shown in diagrams in Figure 4. These results show that the deformation field of each surface has also a wave-like form; maximum amplitude of the buckling of both sides is achieved in the direction of preliminary impact; amplitude of normal deviations increases monotonically with the increase of load and reaches just before fracture the value of +2.4 mm on the inner side, and +1.5 mm on the external one. Thickening field of the panel due to internal delamination, calculated as the difference between the fields of normal deviations of two surfaces, is more complex and reaches before fracture the value of 2.1 mm at maximum. Thickening field has areas of negative thickening, what occurs apparently due to "selecting" of delamination under loading formed after preliminary impact. It is interesting that near the point of preliminary impact thickening of the panel is not observed, indicating the absence of loss of integrity of material in this site.

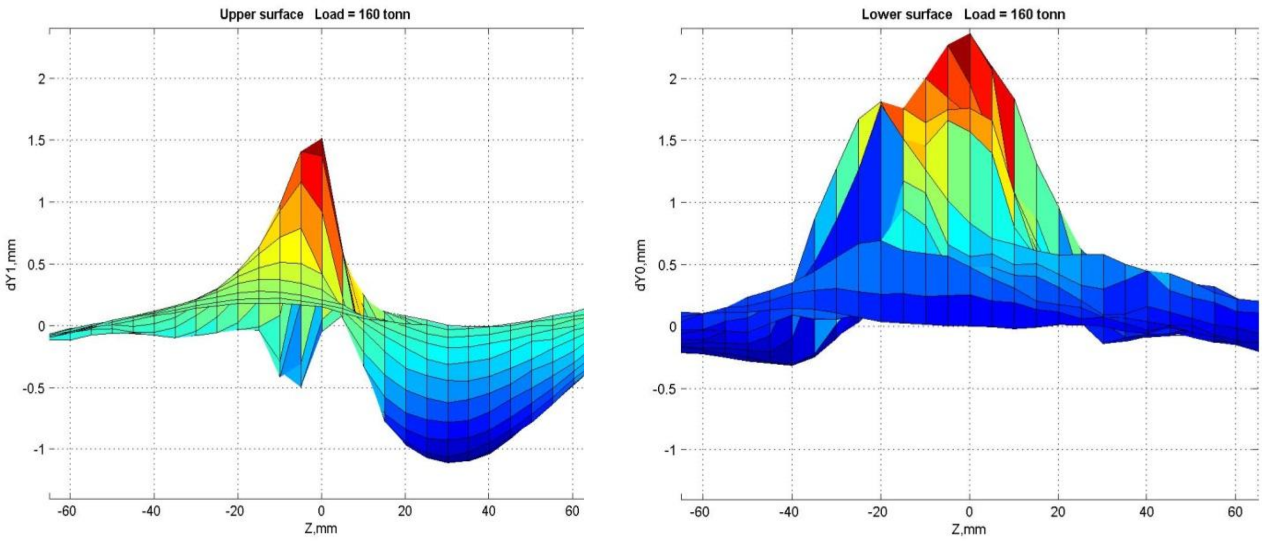


Fig. 4 Normal buckling deformation fields of the external (a) and internal (b) skin surfaces

Figure 5 demonstrates qualitative agreement of delamination zone after impact obtained from ultrasonic inspection (a), with the measured thickening field of the sample (b), indicating that the thickening occurs in the area of preliminary delamination.

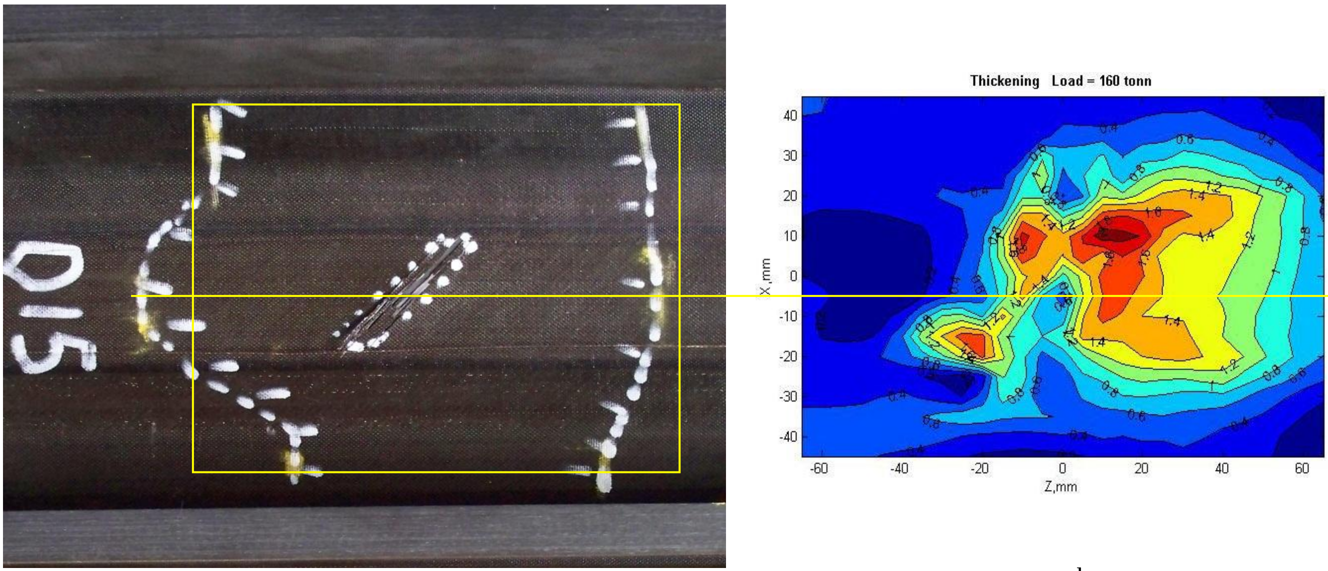


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Fig. 5 Agreement of delamination zone by the results of ultrasonic inspection (a) with the skin thickening field (b)

3 Conclusion

Studies conducted have shown that non-contact optical videogrammetry method is a convenient, highly accurate and promising for research of normal deformation fields of structural elements of aircraft with flat and low curvature surfaces. The method gives a clear picture of the process that can contribute to a more strict interpretation of results of tensometry, while the measurement error does not exceed 0.1 mm/m. In addition, getting such a picture in preliminary measurements makes it possible to optimally place strain gauges in the next stage of testing. The developed method is at the level of world achievements. As for further modernization of the method, currently active work is being conducted to increase its accuracy and improve algorithms of experimental data processing.

4 References

[1] Kulesh V P, Fonov S D (1998) Measurement of parameters of motion and deformation of aircraft model in a wind tunnel by videogrammetry method. *Scientific notes of TsAGI,. v.XXIX, №1-2*. pp 165-176.

[2] Burner A W, Tianshu Liu (2001) Videogrammetric model deformation measurement technique. *Journal of Aircraft, 38 4*, pp 745-754.

[3] Kulesh V P (2004) Non-contact measurements of geometrical shape parameters, motion and deformation of objects in experimental aerodynamics. *Sensors and systems, № 3*, pp 22-27.