Specifics of application of videogrammetric system Vic-3D in aerodynamic experiment

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Abstract. The main objective of this work was testing a possibility of application of commercial videogrammetric system Vic-3D for measuring position and deformation of the aircraft model and its elements in an industrial the TsAGI transonic wind tunnel T-128. The object of research was a model of passenger aircraft with a wingspan of 2010 mm, fixed on the rear sting. The Vic-3D system used for measuring the position and deformation of the aircraft model was applied for the runs with and without flow at the pitch angles range from –3 to +12 degrees. Model was tested in wind tunnel up to Mach number M = 0.853. An algorithm of working with the Vic-3D system was described in the article, some specifics of obtained results were underlined. An additional program to derive bend and twist deformations of a wing was developed. Results of an experiment were given, errors and inaccuracy were analyzed. Recommendations for using the system Vic-3D in an aerodynamic experiment were given.

1. Introduction

The videogrammetry method (VGM) is currently widely used in aerodynamic and strength experiments at TsAGI [1-3]. It is used for panoramic non-contact measurements of distributed parameters of deformations of models in the flow of a wind tunnel or under the pressure of specified loads on the stand. The main principle of the VGM is to find three-dimensional spatial coordinates \{x, y, z\} of a point on the object’s surface from two-dimensional coordinates \{u, v\} of the projection of this point on the digital image. One of the ways to resolve the fundamental problem of uncertainty of restoring the coordinates in space is the method of stereogrammetry, when at least two different images of the object obtained from different angles of view (stereo pair). A connection between the spatial coordinates of the object and the digital coordinates in the images is found with usage of these images [1, 4, 5]. One of the commercial videogrammetric systems is the Vic-3D stereogrammetric system from Correlated Solutions (USA). The Vic-3D system extracted necessary information with use of the method of numerical cross-correlation of digital images of a stereo pair [6, 7].

The purpose of this work was to test the possibility of using the Vic-3D videogrammetric system for measuring the position and deformation of an aircraft model and its elements during testing in the TsAGI transonic wind tunnel T-128.

The distinctive feature of the task was that the transonic wind tunnel T-128 TsAGI is a wind tunnel with perforated test section. Observation and illumination of the model can be carried out only through special optical windows in the walls of the working section. Therefore, one of the
tasks of this experiment was the adaptation of the Vic-3D optical system to the few available optical windows.

2. The Vic-3D stereogrammetric system in the wind tunnel T-128 TsAGI

The Vic-3D system includes:

- two high-speed and high-resolution digital cameras acA2440-75um-Basler-ace with a CMOS sensor 2/3” (matrix resolution 2448×2048 pixels, pixel size 0.00345 mm, 12-bit ADC);
- the light source – LED projector with adjustable brightness;
- two high-speed fiber optic cables, used for connection between cameras and PC-based image-processing system.

![Figure 1](image1.png)

Figure 1. A scheme of location of cameras and lightning source in working section of the TsAGI wind tunnel T-128.

Cameras with their optical axes must be installed at a certain range of angles to each other. It is recommended to position the cameras symmetrically to the specimen so that the projection is an isosceles triangle with an apex angle of 15-45° [6]. Taking into account the requirements for the placement of cameras and the difficult optical access in the closed working section of the wind tunnel T-128, windows № 21 and № 22 were chosen for installing the cameras in the upper wall of the working section № 1 (figure 1). The illumination was provided by an LED projector installed outside the window № 22. The cameras and the projector were oriented towards the left wing. The distances from the cameras to the root section of the wing were approximately 2100 mm and 2300 mm. The convergence angle was approximately 9.3°. As a compromise between the maximum coverage area of the model and the resolution of the camera, a lens with a focal length of \( F = 17 \text{ mm} \) were chosen.
3. Test subject and a grid of markers
The research was carried out using a full model of a passenger aircraft with a wingspan of 2010 mm, mounted on a rear sting. The measurement technique used in the Vic-3D stereogrammetric system implies a special marking of the object’s surface. An irregular "grid" of small-scale points (speckles) or a set of markers (points located at the nodes of a regular computational grid) can be applied on the surface of a model, it depends on the conditions and goals of the experiment.

In this experiment, a technique using local markers was chosen. For this purpose, the left wing was painted with white matte paint, and a grid of local black markers distributed over 11 sections was applied to its surface. In total, 62 markers were placed on the model: 9 – in the first, root section, 7 – in the second, 6 – in the third and 5 – in the other sections.

Markers of calculated size and shape were plotted to the white surface of the model with black paint manually according to a pre-calculated marking scheme. The three-dimensional coordinates of the markers, approximately specified during the plotting with an accuracy of ± 0.5 mm, were additionally adjusted and measured by a coordinate measuring machine in the coordinate system associated with the model in a zero pitch angle.

4. Calibration of the measuring system
A process of calibration of the measuring system is a mandatory procedure in the VGM method. The purpose of calibration is finding the numerical parameters of the equations of the relationship between three-dimensional spatial coordinates \( \{x, y, z\} \) and two-dimensional coordinates \( \{u, v\} \) on the digital image.

The Vic-3D system was calibrated using special plate-type calibration devices. The calibration device was installed in the direct proximity of the model. Its position and orientation were set according to the calibration procedure [6, 7]. In total, 60–80 calibration frames at different positions of the calibration device were recorded. An analysis and processing of calibration images was performed in Vic-3D automatically. Figure 2 shows a view of the Vic-3D software working window with one of the calibration images and the results of the calibration.

![Figure 2. A view of the Vic-3D software program with one of the calibration images and the results of the calibration.](image-url)
5. Features of processing and results

First, the tests were performed without flow with a discrete position of the model pitch angle in the range from -4 to +12°. At each fixed position of the model, 3-5 images were acquired by the Vic-3D system. The measurements with the flow were carried out according to the same program. Runs of the wind tunnel were carried out at Mach numbers range from $M = 0.85$ to 0.95 and the Reynolds number from $3.4 \cdot 10^6$ to $5 \cdot 10^6$. In each run, the pitch angle was varied at constant $M$ and $Re$ numbers. The setting of the measuring system remained unchanged throughout the experiment.

Image processing was performed using special Vic-3D software for each run in batch mode. It included automatic calibration of the Vic-3D system using a flatbed-type calibration device, manual placement of markers in the first image and subsequent placement in all images in automatic mode, calculation of three-dimensional coordinates $x$, $y$, $z$ of all markers in the coordinate system linked to the model in the original condition. The results of this processing stage were values arrays of three-dimensional coordinates (stereo-pairs) of all markers for each readout. To obtain the required parameters $Dx$ and $Dy$ of the bending deformation in two coordinates and the wing twist $Da$, an additional post-processing program was developed in the MatLab software environment. It included the following basic procedures:

- separation of displacements of points of the model caused by the movement of the model as a whole, and due to its wing surface deformation. This separation is based on the assumption that bending and torsional deformations are zero in root section of the wing. The result of this procedure was the parameters of the model position in test section, in particular, the values of the pitch angle of the model;
- calculation of the parameters of bending deformation and angular displacement. This procedure was carried out by aligning the markers coordinates of each section between the undeformed state and the current deformed state by the least-squares method.

The coordinates of the markers obtained in the run without the flow allowed obtaining, in particular, information about the designed twist of the wing. In addition, a comparison was made between the pitch angle values obtained by the Vic-3D and the readings of the pendulum accelerometer installed in the model. Figure 3 shows the comparison of pitch angles measured by the Vic-3D and an accelerometer. A graph of the difference between the Vic-3D pitch angles and the accelerometer readings is demonstrated in figure 4. The systematic difference of approximately one degree may be because the wing root sections have an additional inclination with respect to the fuselage. The root-mean-square (RMS) discrepancy between the results of measuring the pitch angle did not exceed 0.2°. Figure 5 shows a graph of the vertical deviations of the sections $Dy$, characterizing the bend deformation of the wing in the vertical plane, depending on the coordinate $z$. Highlighted in different colors are the vertical displacements obtained at different values of the model pitch angle from -4.1 to +10.5° in the operating launch at the mode $M = 0.85$, $Re = 3.4 \cdot 10^6$.

![Figure 3. Comparison of pitch angles measured by the Vic-3D and an angle sensor.](image-url)
Figure 4. Difference between measured pitch angles of a model by the Vic-3D and an angle sensor.

6. Accuracy of the experiment

In the procedure of calculating the parameters of bending deformation and angular displacement, which was made by the least squares method, the accompanying result is the value of the standard deviation of current coordinates of the markers in the section from their original values. This value of RMS deviation was taken as an indicator of the error of measurements. Analysis of this parameter showed that there was the random component of the error. The reason of this error was the small convergence angle between the cameras which were located in closely spaced optical windows in the working section of the wind tunnel.

Figure 5. A graph of vertical displacement of sections at different pitch angles.

The random error of the measurements by stereogrammetry can be divided into transverse and longitudinal components. The transverse component $\sigma_\parallel$ is determined by the sensitivity limit $\sigma_1$ and $\sigma_2$ of each of two videogrammetric channels. It can be simply estimated by the RMS values

$$\sigma_\parallel = \sqrt{\frac{\sigma_1^2 + \sigma_2^2}{2}}.$$

The longitudinal component $\sigma_\perp$ depends on the convergence angle $2\vartheta$, i.e. the angle of convergence of straight lines to the centers of the objectives of two cameras (figure 6)

$$\sigma_\perp = \frac{\sigma_\parallel}{\tan \vartheta} \approx \frac{\sigma_\parallel}{\vartheta}.$$
Figure 6. Components of an error in the method of stereogrammetry.

The convergence angle between the cameras of the Vic-3D stereogrammetric system in the wind tunnel T-128 was $2\theta = 9.3^\circ = 0.162$ rad. In this case

$$\sigma_e = \frac{\sigma + \sigma_z}{0.081} \approx 12\sigma_z.$$  

This mainly explains more than 10 times higher longitudinal component of the random measurement error by the Vic-3D system in the experiment.

7. Conclusion

Based on the results of the tests carried out in the T-128 wind tunnel, it can be tentatively concluded that it is possible to use the Vic-3D system in an industrial aerodynamic facilities with a closed test section. Systematic measurement errors score acceptable value. However, in order to improve the random component of errors, it is necessary, on the one hand, to study more thoroughly the capabilities of the Vic-3D system through systematic methodological and metrological studies in laboratory conditions, and, on the other hand, to improve the methodology for its application in wind tunnels with a closed test section.

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