FLOW EVOLUTION MONITORING FOR AIRCRAFT ICING STUDY

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ABSTRACT:

Monitoring the evolution of the aerodynamic flow in potentially dangerous conditions is very important to ensure flight safety. Due to the impossibility of experimental study of critical flight conditions in real flights, methods of scaled modeling of flow processes have been developed and are widely used in aerodynamics and hydrodynamics. Aircraft icing is one of the most important processes that pose a threat to flight safety. The presented study is aimed at developing techniques for monitoring of process of aircraft icing and its influence on flow behaviour, that can be used in controlled conditions of aerodynamic/hydrodynamic tube. While available technical means for aerodynamic study does not include the wind tunnel for registration of flow simultaneously with icing process, the proposed framework includes as icing process 3D registration so further modelling this process in a hydrodynamic tube for flow monitoring. The proposed technique includes three phases, that allow to perform comprehensive monitoring of the whole process beginning with 3D registration of ice accretion development and completing with accurate 3D flow evolution monitoring corresponding to icing process.

1. INTRODUCTION

Official statistics based on the analysis of aviation accidents in recent years, report aircraft icing as the predominant external cause of the accident (Cao et al., 2018, McClain et al., 2018, Velandia and Bansmer, 2020). So, the effect of icing on the aerodynamic characteristics of the aircraft attracts a lot of attention from the scientific community. The researches are carried out in several directions: digital modelling of airfoil icing process (Bragg et al., 2002, Hann et al., 2020), ice accretion shape measuring by different techniques, the study of aerodynamic performance degradation as a result of aircraft icing.

The comprehensive study of icing influence on aerodynamics of an aircraft can be divided into two main parts: investigation of icing process depending on air conditions, airfoil shape and other affected factors, and studying of how ice accretion shape influences on aerodynamic performance of the aircraft.

In the field of studying the icing process notable progress has been achieved with development icing wind tunnels, that allow to model air conditions corresponding to ice accretion appearance. Such facilities like NASA icing research tunnel and icing wind tunnel of European Research Establishments in Aeronautics (EREA) provide wide possibility for researches of aircraft icing. They allowed to study the process of airfoils icing depending on airfoil shape, and to use these results for further estimating the aircraft performance in icing conditions.

The results of study of ice accretion development are then used for investigation of flow behaviour in icing conditions. For flow behaviour study aerodynamic and hydrodynamic tunnels are widely used. The similitude concept is the basis for using scaled models in flow study in aerodynamic and hydrodynamic tunnels. The similitude concept provides the adequacy of the results flow modelling to real flight conditions if aerodynamic similarity in terms of such dimensionless similarity criteria as Reynolds number, Mach number, Prandtl number are carried out.

The currents study is aimed at developing the holistic framework for accurate 3D flow evolution monitoring during aircraft icing process. The developed framework (Figure 1) consists of a set of techniques that allows accurate 3D registration of accretion development process in icing research tunnel, reconstruction of accretion shapes at different phases of icing process by rapid prototyping methods, accurate 3D registration and 3D reconstruction of flow evolution along during accretion development based on modelling in a hydrodynamic tunnel.

The main contributions of the study are: (1) the holistic framework for monitoring flow evolution during the process of aircraft icing; (2) the techniques for 3D registration of ice accretion development in controlled condition of icing research tunnel; (3) experimental evaluation of the proposed framework at all phases of aircraft icing study.

2. RELATED WORK

The importance of aircraft icing understanding and the necessity of developing measures to prevent the icing gave a strong impetus to the study of this problem. The research activity areas can be divided into two groups: 1) the studying of the conditions for icing, types and shapes of ice accretion and 2) the analysis of how the icing influences on aerodynamic characteristics of an aircraft.

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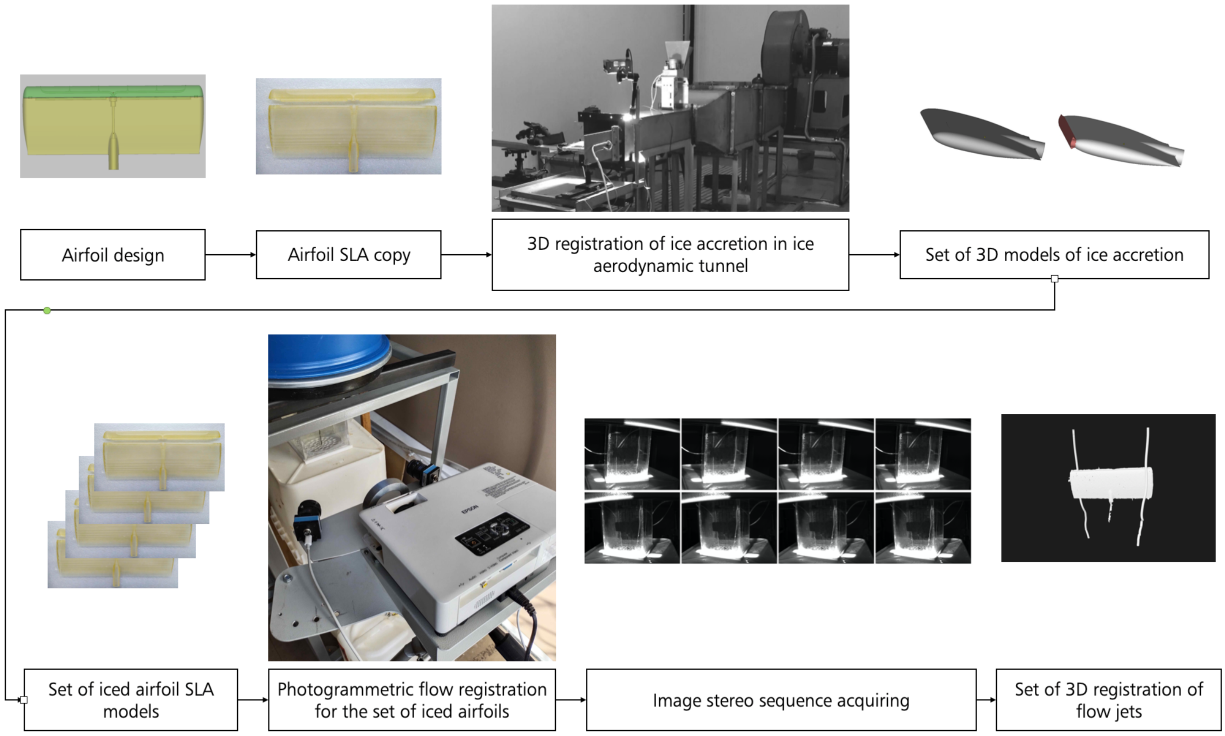


Figure 1. The framework for flow evolution monitoring

Great variety of factors, influenced on aircraft icing, requires comprehensive studying in several ares such as relationship of weather conditions and aircraft characteristics with process of icing and properties of ice accretion; analysis of accidents caused by aircraft icing; flight performance degradation caused by ice accretion growing; measures developing for decrease or eliminate icing. Recent reviews on this topics (Caliskan and Hajiyev, 2013, Cao et al., 2018, Yamazaki et al., 2021) provide wide and comprehensive analysis of current state of aircraft icing problem.

Along with existing icing prognosis techniques based on ambient temperature and humidity data, several research groups develop methods for ice thickness and ice shape measuring. Analysis of light diffusion on airfoil surface (Ikiades et al., 2007) allows to detect ice and to recognize its type. Experimental evaluation showed that spatial distribution of the specular and scattered components of light provides information for classifying ice type and estimating its thickness.

The shape of the ice growths has a more significant effect on the aerodynamic characteristics than its thickness. The use of contact measurement methods (like casting and mold) to register the shape of ice disrupts the icing process and does not allow tracking its development over time (Hansman et al., 1988). Various methods of contactless measurements such as microwave, ultrasonic, optical were applied for 3D registration of the ice shape. Despite the indisputable advantages of the optical methods such as high accuracy and high resolution of the shape measuring, the non-diffusive reflective properties of the ice create a problem for their applying in this task.

Special techniques such as applying opaque spray to provide diffusive reflectance of ice accretion are successfully used for the ice shape 3D registration. Several studies aimed at 3D reconstruction of ice accretion shape using thermal imaging (Gong and Bansmer, 2015, Knyaz et al., 2021a) showed that this technique can be used for accurate ice shape 3D registration, but currently provide worse performance comparing with visible range measurements.

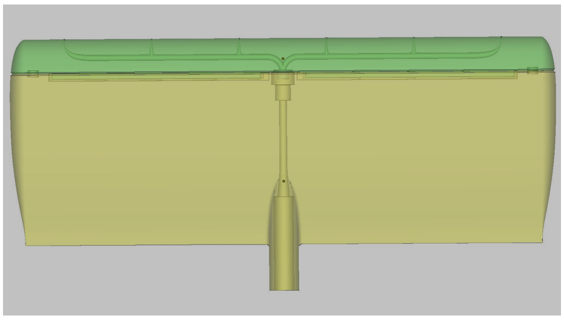
Researches for 3D registration of ice accretion shape (Broeren et al., 2010, Pouryoussefi et al., 2016) addresses obtaining digital 3D models, that reflect the state of the accretion at different stages of icing. These accretion 3D models then are used for experiments in aerodynamic tunnels (Lee et al., 2019), aimed at analysis the influence of different accretion types and thickness on aerodynamic characteristics of an aircraft.

3. MATERIAL AND METHODS

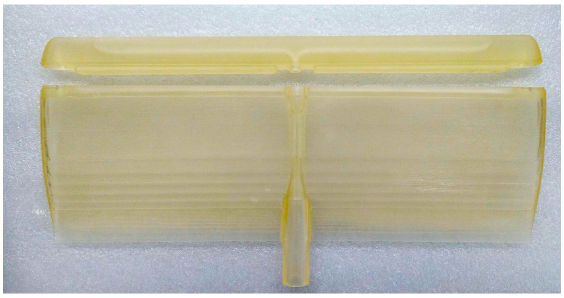
The icing process depends on several factors, such as air condition, flight mode and the shape of airfoil. Therefore the first phase of the study is producing the scaled model of the airfoil under consideration. The stereolithography (SLA) technique was used for producing the accurate hard copy of CAD model of the airfoil (Figure 2), that was investigated during the experiments. To provide the possibility of modelling accretion of different shapes, the front edge of the airfoil model is made replaceable (Figure 2(a)).

Using the different replaceable parts of the airfoil model, that correspond to different phases of airfoil icing (Figure 2(b)), allows to monitor the evolution of flow behaviour according to the level of accretion.

The shape of the accretion, that grows on the airfoil in icing condition, was studied at ice aerodynamic tunnel (IAT).



(a) CAD model of the airfoil with replaceable part



(b) Stereolithography model of the airfoil

Figure 2. Model of the airfoil and its SLA copy used in experiments

3.1 Accretion development monitoring

The experiments on ice accretion shape developing was performed using ice aerodynamic tunnel (IAT) of Central Aero-Hydrodynamic Institute (TsAGI). The ice aerodynamic tunnel (Figure 3) is an open-loop fan-type wind tunnel, that includes systems for crystal and water spray injection. The air, cooled to -18^oC, is injected into working part of the tunnel forcing ice accretion to appear on the airfoil.

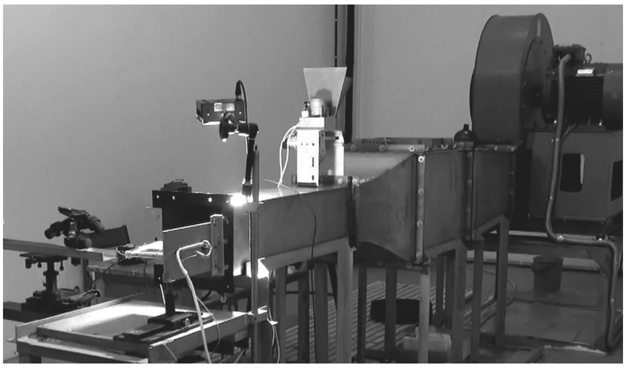


Figure 3. Icing wind tunnel

Two techniques for ice accretion shape registering were explored during the experiments (Knyaz et al., 2021a). FIrst technique utilized accretion imaging in thermal range acquired in thermal structured lighting. Thermal MH SM567 camera was used for image acquisition, Iradion® Infinity CO_2 laser providing object lighting in thermal range.

The second technique is based on image acquisition in visible range. The two-camera configuration of Mosca photogrammetric system (Knyaz, 2015), equipped with DMK 37BUX273 USB 3.1 monochrome industrial cameras, was used for 3D reconstruction of ice accretion shape. General specifications of the thermal and visible cameras are given in Table 1.

Table 1. Thermal and visible camera specifications

Parameter	MH-SM567	DMK 37BUX273
Type	Uncooled FPA	1/2.9" CMOS
FPA format	640×480	$1,440 \times 1,080$
Pixel pitch	$17\mu m$	$4.45\mu m$
Sensitivity	$\leq 150\ mK$	
Frame rate	50Hz	up to 238 fps
Spectral range	$8 – 14\mu m$	$0.4 – 0.95\mu m$
Lens	12.8 mm	12 mm

Due to non-diffusion light reflection from ice (snow) it is not possible to use structured light technique for ice shape 3D reconstruction. Therefore special opaque spray was used for providing diffuse characteristics of the surface and allowing to apply structured light technique for 3D shape reconstruction.

Both methods were evaluated for 3D reconstruction of ice accretion and demonstrated comparable accuracy. Experiments have shown, that 3D ice shape reconstruction using thermal imaging provides acceptable accuracy of 3D measurements based on calibration of the thermal imaging camera. Meanwhile this method is more expensive and complicated in comparison with ice shape 3D reconstruction by visible range system when applying opaque spray for providing diffuse reflection property of the reconstructed surface. Therefore visible range configuration of photogrammetric system was applied for 3D registration of the accretion developing in the icing aerodynamic tunnel.

The airfoil SLA model was sequentially placed in the ice aerodynamic tunnel for a some time period and then scanned to register the accretion shape at this phase. As a result, a set of 3D models of iced airfoil was obtained. This set was then used to produce SLA models of ice shapes, that applied for flow changes monitoring during ice accretion developing. Stereolithography models of the clear airfoil and the airfoil with ice accretion at one of the icing phases are shown in Figure 4.

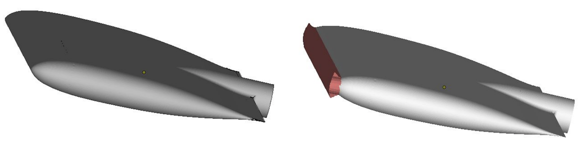


Figure 4. CAD model of the airfoil without/with accretion

The changes in flow caused by the airfoil acing are studied in hydrodynamic tunnel using this set of SLA models.

3.2 Flow behaviour monitoring

Flow changes, caused by transformations of the airfoil shape due to icing, was studied using hydrodynamic tunnel. The possibility of applying hydrodynamic tunnel for the study is provided by similarity of realflow and the model flow, and the advantage of hydrodynamic tunnel is slow flow velocity Based on similitude concept the adequateness of results is provided by Reynolds number equivalence for model and real processes.

For the framework developing a laboratory hydrodynamic tunnel has been constructed. It models the conditions of experiments in the hydrodynamic tunnel HDT-400 of Central Aero-Hydrodynamic Institute (TsAGI), where the developed techniques are to be implemented.

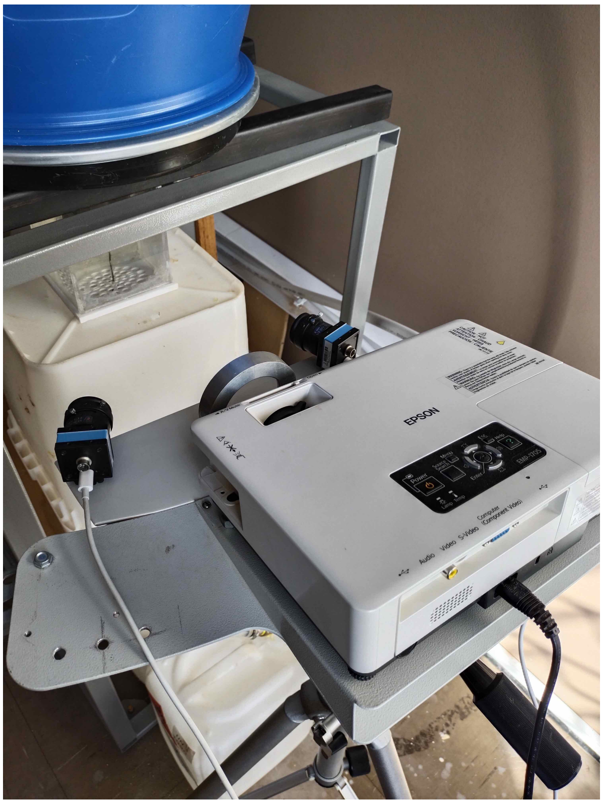


Figure 5. Laboratory hydrodynamic tunnel and photogrammetric system for 3D measurements

The laboratory hydrodynamic tunnel consists of a water tank located under the workspace to accommodate the test model, and a reservoir for collecting waste water (Figure 5). It allows to study all necessary phases of 3D monitoring process, beginning with photogrammetric system calibration and completing with 3D flow reconstruction. The conditions of experiments corresponds to the tests in the hydrodynamic tunnel HDT-400.

The photogrammetric 3D measurement system consists of two DMK 37BUX273 high resolution and high speed cameras equipped with 6 mm lenses and a structured light projector (Figure 5).

To provide high accuracy of 3D measurements of flow jets a model of imaging in case of several optical media has been developed. The imaging model (Knyaz et al., 2021b) exactly considers the light ray path from an object point A to the corresponding image point a in the image plane, taking in account light refraction at different optical medias interfaces.

The ray path (Figure 6) consists of three parts, that can be described by three vectors $\mathbf{r^1}$ for air, $\mathbf{r^2}$ for glass, and $\mathbf{r^3}$ for liquid.

Figure 6 presents the systems of coordinates, that are considered in the study. Object coordinate system $OXYZ$ is related to studied object, image system of coordinates $Cxyz$ is related to the camera, and glass system of coordinates $\Omega X_g Y_g Z_g$ is related to glass wall of the working part.

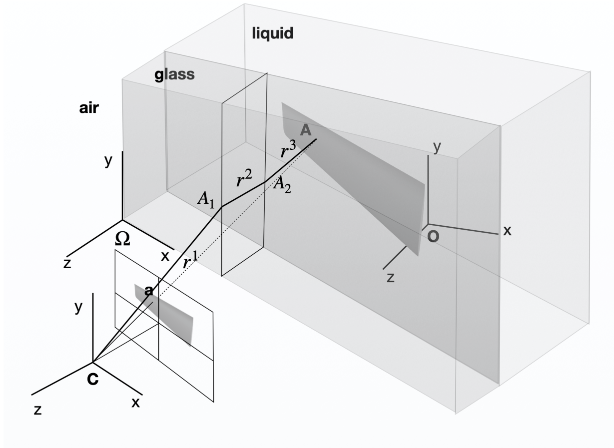


Figure 6. Ray path through several optical media interfaces.

For each vector $\mathbf{r^1}$, $\mathbf{r^2}$, $\mathbf{r^3}$ the equations defining its position in object coordinate system are derived using Snell law in form:

$$\mathbf{r^1} = \begin{pmatrix} X_1 \\ Y_1 \\ Z_1 \end{pmatrix} = \mathbf{R^T} \cdot \begin{pmatrix} x \\ y \\ -c \end{pmatrix} \quad (1)$$

$$\mathbf{r^2} = \begin{pmatrix} r^2_x \\ r^2_y \\ r^2_z \end{pmatrix} = \begin{pmatrix} r^1_x \cdot tg(\phi_2) \\ r^1_y \cdot tg(\phi_2) \\ r^1_z \end{pmatrix}, \; sin(\phi_2) = \frac{1}{n_1} \cdot sin(\phi_1) \quad (2)$$

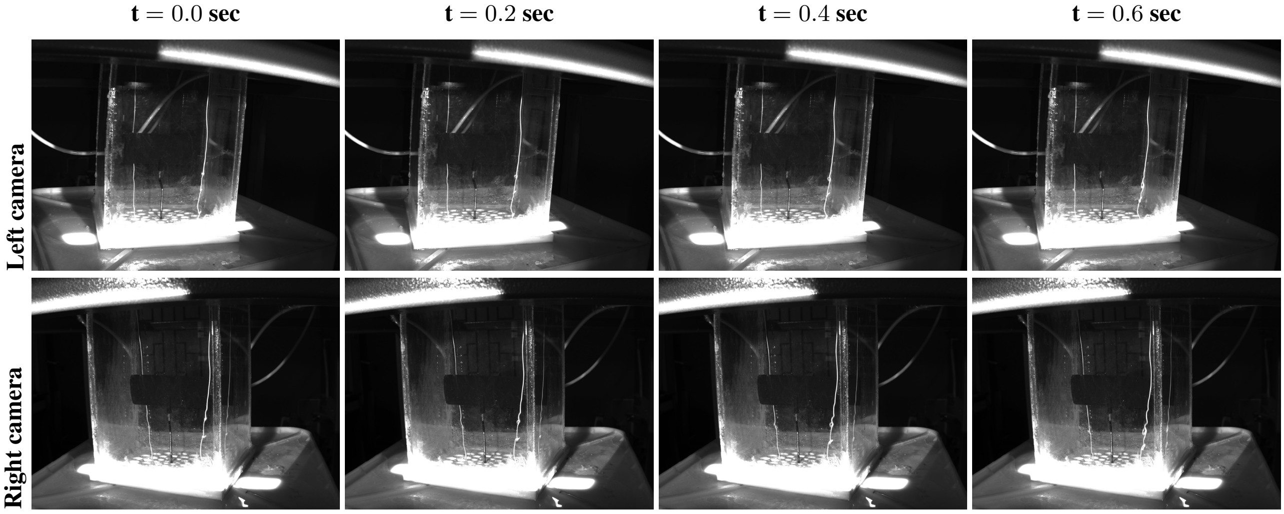
$$\mathbf{r^3} = \begin{pmatrix} r^3_x \\ r^3_y \\ r^3_z \end{pmatrix} = \begin{pmatrix} r^2_x \cdot tg(\phi_3) \\ r^2_y \cdot tg(\phi_3) \\ r^2_z \end{pmatrix}, \; sin(\phi_3) = \frac{n_1}{n_2} \cdot sin(\phi_2) \quad (3)$$

The coordinates of origin of each vector C, A_1, A_2 are defined using parameters of camera exterior orientation and conditions of intersection with glass planes, the refraction indexes of glass n_1 and water n_2 are taken as known or determined during calibration (Knyaz et al., 2021b). The system of equations for light ray path from object point A to corresponding image point a can be written in form:

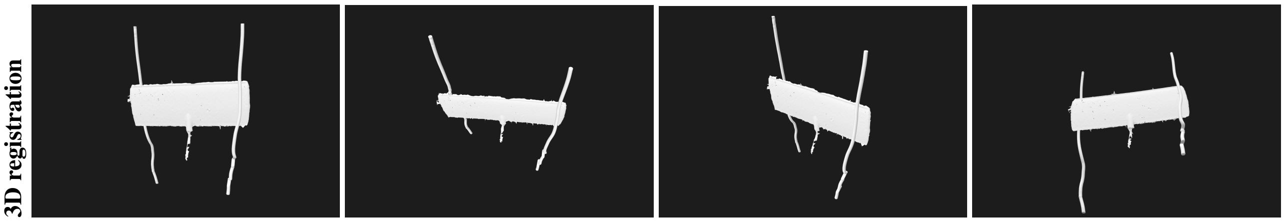
$$F(\boldsymbol{x}_a, n_1, n_2, \boldsymbol{X}_\Omega, \boldsymbol{X}_A - \boldsymbol{X}_C) = 0, \quad (4)$$

The equation 4 establish the relations between object point $\boldsymbol{X}_A$, the center of projection $\boldsymbol{X}_C$, and image point $\boldsymbol{x}_a$. So it is some kind of analog of standard photogrammetric co-lnearity equations and can be used photogrammetric system calibration and object points 3D coordinates determination.

To provide high accuracy of 3D measurements special calibration procedure was developed for multi media imaging case. This procedure uses equations 4 to establish the relation between reference points of a test field and their observations and accounts for image distortions in form of Brown-Conrady model (Brown, 1966, Beyer, 1992)



a) Image sequences acquired by left and right cameras



b) Different views of 3D reconstructions of flow jets

Figure 7. Image sequences acquired by left and right cameras and results of 3D reconstruction of flow jets.

$$\Delta_x = a_0 \cdot y + x(a_1 r^2 + a_2 r^4 + a_3 r^6) + a_4(r^2 + 2x^2) + 2a_5 xy;$$
$$\Delta_y = a_0 \cdot x + y(a_1 r^2 + a_2 r^4 + a_3 r^6) + a_5(r^2 + 2y^2) + 2a_4 xy;$$

with $r^2 = x^2 + y^2$.

and

x_a, y_a – coordinates of a point on the image,
$a_0, ..., a_5$ – camera interior orientation parameters:
a_0 – coefficient of affine distortion;
a_1, a_2, a_3 – coefficients of radial distortion;
a_4, a_5 – coefficients of tangential distortion.

The results of photogrammetric system calibration demonstrated high accuracy of 3D measurements and proved the adequacy of the developed imaging model. The calibration accuracy was evaluated by comparing the results of reference surface 3D reconstruction in single optical media case and several optical media (air, glass, liquid) case. Airfoil stereolithography model was used as a reference surface for the evaluation. The average distance between two scanned surfaces serves as the metric of correspondence of the surfaces (Knyaz and Zheltov, 2017). The results of the alignment of the surfaces using Cloud Compare[1] software are presented in Figure 8.

[1] `https://www.cloudcompare.org`

Figure 8 demonstrates high level of correspondence between two surfaces, thus proving high quality of the developed imaging model and calibration procedure.

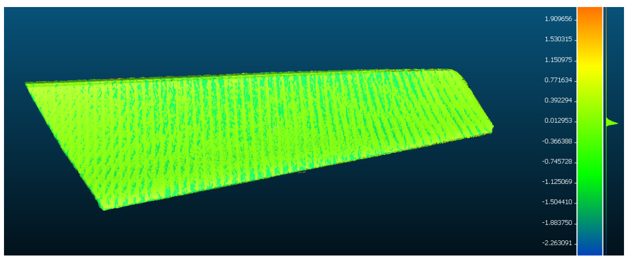


Figure 8. Results of measurement comparison for two sets of the calibration parameters

The next phase of the framework evaluation was experimental flow jets 3D registration at the laboratory hydrodynamic tunnel. For flow 3D registration the Mosca photogrammetric system (Knyaz, 2015) calibrated for optical multimedia imaging was applied. Figure 7 presents a sequence of the stereo pairs of images, obtained from left and right cameras and used for dynamic 3D reconstruction.

The obtained image sequences were processed for 3D reconstructing of the flow jets. To provide robust detection of the flow jets in the images, firstly, images of the hydrodynamic tunnel working part were captured. They afterwards were used as background images, subtracted from flow jets images to robustly identify the flow jets.

For 3D reconstruction of the shape of the flow jets, parameters the epipolar geometry technique based on known parameters of the exterior orientation of the cameras. The 3D coordinates of determined corresponding points were calculated using imaging multimedia model (Eq. 4).

A set of stereo sequences was acquired for different levels of ice accretion developing. The sequence of ice accretions 3D models, obtained during 3D registration of the accretion growing process in ice aerodynamic tunnel was used for for this purpose. Photogrammetric processing of the stereo sequences allows to 3D reconstruct the evolution of the flow during ice accretion growing. The analysis of 4D registrations of flow behaviour allows to make decisions on critical conditions of aircraft icing and to develop measures for preventing dangerous flight conditions.

4. CONCLUSION

The completed framework for flow 3D monitoring during an airfoil icing process is developed. It includes the 3D registration of ice accretion developing in time at the icing aerodynamic tunnel, producing a set of SLA models reproducing ice accretion growing, and 3D registration of flow evolution in time according icing process.

Photogrammetric techniques are developed for each phase of flow evolution monitoring. They provide high accuracy of 3D measurements as for ice accretion registration, so for flow jets 3D tracking in the hydrodynamic tunnel. Experimental evaluation of the proposed framework at all phases of aircraft icing study showed the readiness for implementation in experimental process.

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