# Photogrammetric 3D Measurements and Visualization of Flow in Hydrodynamic Tunnel

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**Abstract**

Flow visualization is an important mean for studying flow processes in aerodynamics and hydrodynamics. It allows obtaining qualitative valuable information about flow behaviour, that is needed for understanding of aerodynamic performance of an aircraft, especially in critical conditions. With growing advances in 3D optical measuring techniques, accurate 3D registration and measurements of fast developing processes became possible. The paper addresses the problem of accurate metric 3D reconstruction of flow in hydrodynamic tunnel that is necessary for studying aerodynamic process in aircraft icing conditions. It presents the techniques developed for optical measurement system calibration and for accurate flow 3D registration, and the results of laboratory flow 3D reconstruction and visualization. Experimental evaluation of the developed techniques in laboratory hydrodynamic tunnel demonstrated high accuracy of 3D measurements and readiness for applying in aircraft icing study.

**Keywords**

image-based 3D measurements, hydrodynamic tunnel, aircraft icing, multimedia imaging, 3D visualization.

## 1. Introduction

Modern techniques for aero- and hydrodynamic processes study widely explore physical modelling in aerodynamic and hydrodynamic tunnels for analysis of aerodynamic characteristics of existing and prospective air and marine vehicles. They allow to determine aerodynamic forces and momentums that act on aircraft for various flow velocities and aircraft evolutions. But besides knowing values of forces and momentum it is important

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to have reliable information about flow characteristics and behaviour in different flight conditions.

Physical modeling in aerodynamics is based on the similitude concept, that provides the correspondence of modeling results to the results of natural experiments in case of equivalence of similarity criteria. In aerodynamics such dimensionless criteria are Reynolds number, Mach number and Prandtl number. Moreover basing on similitude concept, aerodynamic process can be studied in hydrodynamic tunnel, thus taking the advantage of studying flow at low velocities.

To obtain qualitative information about the flow process in aerodynamics and hydrodynamics, various methods of visualization of flow are utilized, including the use of colour flue gases and liquids, light particles or filaments. But for adequate understanding and predicting flow behaviour in different conditions, it is more important to have not only qualitative, but quantitative data of flow characteristics. Recent advances in optical 3D measuring methods allows registering and measuring fast developing processes, being the tool for non-invasive and accurate 3D study for wide spectrum of applications. To obtain accurate 3D measurements in hydrodynamic tunnel (Figure 1) it is necessary to account light refraction effects at the optical media interfaces.

The paper presents the current stage of the project aimed at developing techniques and tools for aircraft icing study by vision-based methods. It is based on the performed researches on optical system calibration for 3D measurement in optical multi media condition and developing a photogrammetric system for accurate 3D measurements and registration of flow in hydrodynamic tunnel.

## 2. Related work

Visualization extends the frame of scientific research, providing an opportunity to present data in various forms for comprehensive and versatile analysis. The support of visualization by vision-based methods for 3D reconstruction and texturing is very important in case of visualization of real objects of complicated shape [1, 2, 3] or processes of complex nature and behaviour [4, 5, 6]. A particular demand for vision-based 3D reconstruction exists in aerodynamic and hydrodynamic researches, where visualization plays important role due to the nature of the studied processes.

Recent advances in optical 3D registration and measuring techniques provides a background for not only qualitative, but also for quantitative analysis of flow process. The accuracy of optical 3D measurements is based on calibration, that allows to define parameters of imaging model needed for 3D measurements. The methods for calibration of photogrammetric 3D measurement systems are well-established and proved by scientific and industrial practice [7, 8]. Meanwhile, when applying photogrammetric 3D measuring techniques for flow studying in hydrodynamic tunnel, it is necessary to take into account light refraction at optical media boundaries separating flow from optical measurement system. A set of methods is developed for compensating distortion, related to refraction. Among them applying special optical elements, like prisms filled with water, to provide light running through the optical interface at $90^o$ angle, thus making aberrations to

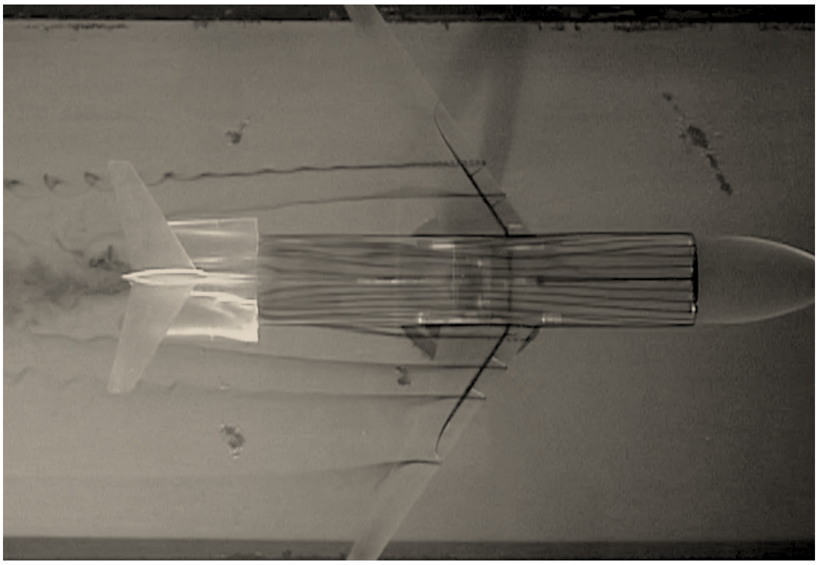


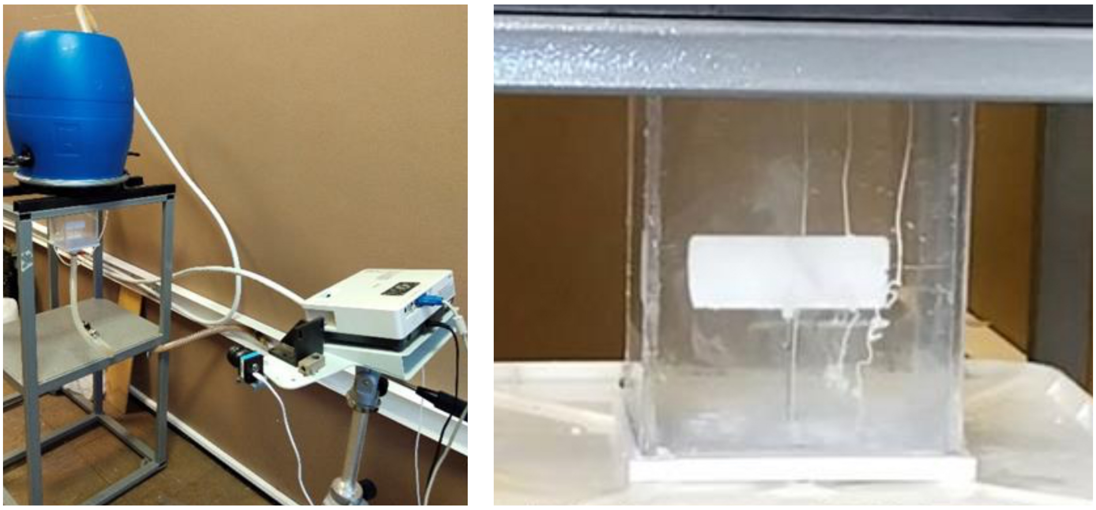
**Figure 1:** Flow visualization in hydrodynamic tunnel

be negligible [9]. Such technique is often applied in the case of fluid flow analysis using the methods of stereoscopic particle velocity measurements (PIV – particle image velocimetry) [10].

For some multimedia optical measurements application a equitable approach is to "absorb" refraction effects by the estimated calibration parameters of the camera [11]. Such approach is reasonable for the cases when the main effect of refraction is radially symmetric relative to the principal point. The "absorbing" technique gives appropriate description of the distortion model for the case of optical axis of the camera being close to perpendicular to the optical interface plane. Unfortunately, the method of "absorbing of refraction effects" always has some systematic errors, that are not accounted in the imaging model. The effect of refraction invalidates the assumption that the camera has a single center of projection [12], which is the main assumption for such model.

Some other approaches offer solutions for geometric correction by introducing a virtual projection center [13] or a two-stage correction [14], including an initial standard calibration in the air, followed by the introduction of additional parameters describing the effects of refraction at the boundaries of optical media.

For the current study accurate imaging model for the case of image acquisition through two optical media interfaces was developed [15]. It considers the ray paths from a given object point to the image plane and consists of a system of equations, providing this relation.



(a) Common view of the laboratory setup (b) Working part with mounted stereolithography model of a wing and coloured jets

**Figure 2:** Laboratory setup for 3D visualization technique evaluating

# 3. MATERIALS AND METHODS

## 3.1. Hardware configuration

Hydrodynamic tunnel provides an indubitable advantage in research of flow motion (Figure 1). This advantage is low speed of the flow (which corresponds flow velocity of air in real conditions).

The physical modeling of flow process in aircraft icing conditions is to perform in hydrodynamic tunnel HDT-400 of Central Aero- and Hydrodynamic Institute (TsAGI). HDT-400 hydrodynamic tunnel is designed for flow studying at very slow velocities, thus providing ”slow-motion” playing of real aerodynamic flow behaviour. To perform preliminary experiments for evaluating the developed techniques a special laboratory setup was created (Figure 2).

Before beginning experimental works in HDT-400 hydrodynamic tunnel, laboratory tests were performed for evaluation of the developed techniques and estimating the accuracy of 3D measurements. The laboratory setup that models HDT-400 was made. It has vertical design similar HDT-400 with a working part with dimensions $110 \times 110 \times 200$ $mm$. A water tank is mounted above the working part, having a set of injectors for colouring flow jets during tests.

The common view of the laboratory setup is shown in Figure 2(a), and the working part with mounted stereolithography model of a wing is presented in Figure 2(b).

For 3D flow registration and accurate measurements the photogrammetric system ”Mosca” [16] was used. The two-camera configuration of ”Mosca” photogrammetric system was applied for the study, the photogrammetric software being modified for

**Table 1**
DMK 37BUX273 camera specification

| Parameter | Value |
|---|---|
| Sensor type | CMOS Pregius |
| Format | 1/2.9" |
| Dynamic range | 10 bit |
| Resolution | $1,440 \times 1,080$ |
| Pixel size | $3.45\ \mu m \times 3.4\ \mu m$ |
| Frame rate | up to 238 fps |
| Shutter | $1 \mu s$ to 30 $s$ |
| Lens | 6 $mm$ |

implementing the developed algorithms for conditions of light ray passing two optical media.

The optical 3D measurement system consists of two DMK 37BUX273 cameras equipped with the IMX273LLR Sony CMOS sensor, and Epson EMP-1705 projector of structured light mounted on a rigid platform, providing stable exterior orientation. Main technical characteristics of the cameras are given in Table 1.

## 3.2. Imaging model for two optical media interfaces

To perform accurate 3D measurements in case of multi-media optical environment it is necessary to account for light refraction at optical media interfaces. Accurate imaging model was developed at the previous stages of the study [15] for this case. The developed mathematical model describes imaging for the case when light ray from object point $A$ to the corresponding image point $a$ refracts at two optical interfaces: "air-glass" and "glass-liquid".

The ray path (Figure 3) for this case can be presented as three vectors $\mathbf{r^1}$, $\mathbf{r^2}$, $\mathbf{r^3}$ for air, for glass, and for liquid correspondingly.

Figure 3 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.

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:

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

$$\mathbf{r^2} = \begin{pmatrix} r_x^2 \\ r_y^2 \\ r_z^2 \end{pmatrix} = \begin{pmatrix} r_x^1 \cdot tg(\phi_2) \\ r_y^1 \cdot tg(\phi_2) \\ r_z^1 \end{pmatrix}, \ sin(\phi_2) = \frac{1}{n_1} \cdot sin(\phi_1) \tag{2}$$

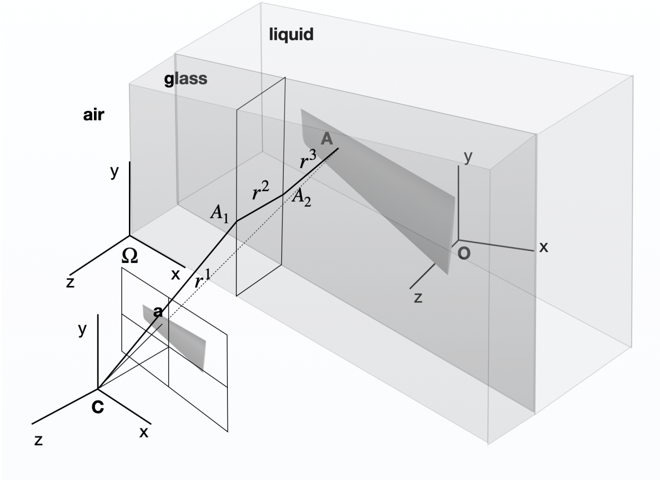



**Figure 3:** Systems of coordinates and the path of light ray.

$$\mathbf{r^3} = \begin{pmatrix} r_x^3 \\ r_y^3 \\ r_z^3 \end{pmatrix} = \begin{pmatrix} r_x^2 \cdot tg(\phi_3) \\ r_y^2 \cdot tg(\phi_3) \\ r_z^2 \end{pmatrix}, \; sin(\phi_3) = \frac{n_1}{n_2} \cdot sin(\phi_2) \tag{3}$$

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 [15]. The system of equations for light ray path from object point $A$ to corresponding image point $a$ can be written in form:

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

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. The non-linear distortion parameters are accounted as additional terms $\Delta_x, \Delta_y$ in the equation 4. These terms are taken in form of Brown-Conrady model [17]:

$$\Delta_x = a_0 \cdot y + x(a_1 r^2 + a_2 r^4 + a_3 r^6) + a_4(r^2 + 2x^2) + 2a_5 xy; \tag{5}$$

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

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

Here

$x_a, y_a$ – coordinates of a point on the image,

$a_0, ..., a_5$ – camera interior orientation parameters:

**Table 2**
Interior orientation parameters

| Parameter | Calibration parameters | | | |
|---|---|---|---|---|
| | calibration stand | | hydrodynamic tunnel | |
| $m_x,\ mm$ | 0,00343588 | 0,003437963 | 0,00343612 | 0,00343903 |
| $m_y,\ mm$ | 0,00343487 | 0,003437819 | 0,00343516 | 0,00343804 |
| $x_p,\ pix$ | 742,12 | 760,87 | 734,77 | 740,07 |
| $y_p,\ pix$ | 587,22 | 578,64 | 618,09 | 555,33 |
| $a_0$ | -0,0005583931 | -0,0004862325 | -0,0005524741 | -0,0005100927 |
| $a_1$ | 0,0120703300 | 0,0116045100 | 0,0112192311 | 0,0119018751 |
| $a_2$ | 0,0004580167 | 0,0003427741 | 0,0004681763 | 0,0003358998 |
| $a_3$ | -0,0000339890 | -0,0000381674 | -0,0000330094 | -0,0000401097 |
| $a_4$ | -0,0000171022 | -0,0001142789 | -0,0000165125 | -0,0001193499 |
| $a_5$ | 0,0001381050 | -0,0001101241 | 0,0001424769 | -0,0001050232 |

$a_0$ – coefficient of affine distortion;
$a_1, a_2, a_3$ – coefficients of radial distortion;
$a_4, a_5$ – coefficients of tangential distortion.

The vector $\boldsymbol{v}_e^l = (x_p, y_p, m_x, m_y, a_0, ..., a_5)^T$ of interior orientation parameters is estimated by calibration procedure [15]. $\boldsymbol{v}_e^l$ includes coordinates of principal point, image scales and additional parameters correspondingly, spatial coordinates of reference points being known by independent precise measurements. The unknown parameters are determined by least mean square estimation using image coordinates of a set of the test field reference points as observations.

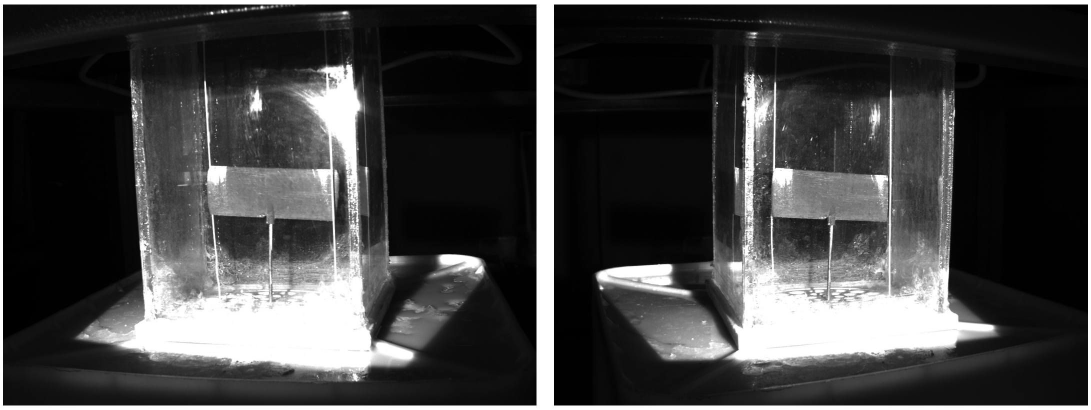
## 4. Experimental results

The developed methods for accurate 3D measurements were tested using the laboratory setup. At the first phase of the laboratory study the developed calibration technique [15] was applied for determination of interior orientation parameters of the photogrammetric system. The results of system calibration at laboratory hydrodynamic tunnel (Figure 2(a)) in comparison with calibration at the special multi-media calibration stand [18] are presented in Table 2.

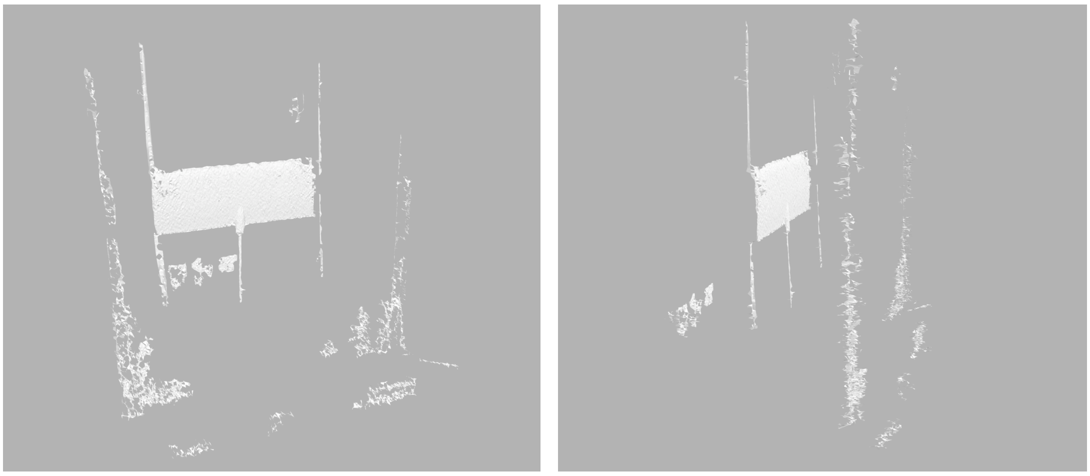
It is worth to note that the estimated interior orientation parameters are very close to those ones determined during experimental system calibration at the special multi-media calibration stand.

At the second phase of laboratory study 3D registration and 3D reconstruction of flow jets was carried out by the photogrammetric system. Figure 4 shows a stereo pair of images from left and right cameras and the results of flow jets 3D reconstruction.

3D scanning technique was used to obtain 3D reconstruction of the working part of the laboratory hydrodynamic tunnel, including the SLA-model of a wing. To reconstruct 3D model of the flow jets a special procedure was applied, that includes (1) acquiring



(a) Stereo pair of the flow in the working part of the laboratory setup



(b) 3D reconstructions of flow in working part of the laboratory setup

**Figure 4:** Stereo pair of the flow and 3D reconstruction of flow in the working part of the laboratory setup

images of the working part without flow jets (background images), (2) acquiring images of the working part with flow jets, (3) separating of the flow jets from background, and (4) 3D reconstruction of the detected flow jets using photogrammetric technique.

Figure 4(b) demonstrates one frame from a sequence of flow jets 3D registration. The developed technique allows to visualize and to analyze the 3D evolution of flow in time.

## 5. CONCLUSION

The current phase of the study of flow in hydrodynamic tunnel by photogrammetric techniques addresses to experimental assessment of the developed optical 3D measurement techniques in laboratory conditions. For this purpose previously developed methods for optical system calibration and optical 3D measurements were implemented in "Mosca" photogrammetric 3D measurement system, and a set of experiments was performed at specially designed laboratory hydrodynamic tunnel.

The experiments proved the high accuracy of optical 3D measurements by modified "Mosca" photogrammetric system in case of optical multi-media environment. A set of experimental 3D registration and 3D visualization of the flow jets in laboratory hydrodynamic tunnel was carried out, that demonstrated the high potential of the developed techniques for flow behaviour study in hydrodynamic tunnel, including 3D visualization of flow evolution in time.

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