Identification of aircraft aerodynamic derivatives based on photogrammetry and computational fluid dynamics

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Abstract. Nowadays, Computational Fluid Dynamic (CFD) analysis is one of the most affordable techniques to determine the aerodynamic characteristics of an aircraft. It allows a development of advanced flight controllers. However, the accuracy of this technique depends on the input parameters such as the solid model. This paper describes a methodology to estimate aerodynamic derivatives of a Cessna 182 aircraft based on solid model established by using photogrammetry technique. 312 images have been taken using Canon D750 camera with a 24 mm lens. A dense point cloud of the aircraft was generated using MicMac photogrammetry software. Then, the aircraft 3D-geometry was extracted in order to create the CAD model. Afterwards, parameters such as lift and drag coefficients were estimated at different angles of attack using Ansys Fluent software. The simulation results show that the lift and drag increase up to stall angle, then the lift starts to decrease. These results matches the theoretical ones.

Keywords: Photogrammetry, 3D modeling, CFD, Aerodynamics, Ansys.

1. Introduction
The State of the art in aircraft modeling has been continuously evolving in terms of various techniques developed to determine the aerodynamic derivatives on which lies the development of a robust flight controller. Nowadays different approaches are able to determine aerodynamic parameters such as wind-tunnel tests [1], [2], or numerical methods called computational fluid dynamics analysis (CFD) which are based on resolving the equation of fluid dynamic, [3] [4].

In most instance, CFD analysis approach is widely used. On one hand it relays mainly on affordable computing equipment. On the other hand, applications and software with CFD capabilities are more available, e.g. Ansys Fluent, Solidwoks, which can be extremely useful for researchers and engineers to accurately predict the aerodynamic characteristics of an aircraft during different flight phases. However, to set up a CFD analysis a specific procedure should be respected. One of the biggest hurdles in this process is to provide an accurate geometric model as an input, either 3-D or 2-D model.

The main objective of this paper is to propose a process for obtaining a 3D model based on the 3D acquisition technique, such as laser scanning or photogrammetry.

Here is an overview of the organization of this paper: Section 2 gives an overview of the aircraft mathematical model. Section 3 presents different approaches that can be used to estimate the aerodynamic coefficients and section 4 focuses on CFD method. A brief overview of the photogrammetry workflow is provided in section 5. Section 6 then discusses the methodology used to extract the aerodynamic derivatives using photogrammetry acquisition. Finally, in section 7, an
application is conducted to estimate the aerodynamic parameters of a preselected aircraft, Cessna 182, and results are discussed.

2. Aircraft mathematical model

In order to determine an accurate model of an aircraft, preliminary knowledge of geometry, static and dynamic characteristics is required. In addition, during the development of the flight controller, it is necessary to know the physical, inertial and aerodynamic characteristics of the aircraft. The aircraft mathematical model can be exhibited as a state-space representation. It is a mathematical model of physical system described as a set of input, output, and state vectors related by first-order differential equation [5].

The determination of aircraft’s equations of motion requires the definition of coordinate systems in which the forces and moments acting on the aircraft are conveniently defined and the states (e.g. position, velocity, acceleration, and attitude) are adequately described [6]. In essence, there is 07 different coordinate systems: Earth-centered Earth-fixed frame (ECEF), Earth-centered inertial frame (ECI), Geodetic coordinate system, Tangent plane coordinate system (LTP), Body-Fixed frame \{b\}, Wind frame and Stability frame. In this paper, all equations are expressed in both Body Fixed frame and Local Tangent plane coordinate system.

Local Tangent Plane Coordinate System, usually marked with the subscript \{u\}, is fixed to the surface of the Earth with two of its axes attached to the plane tangent to the surface. The frame’s x-axis and y-axis are in the tangent plane and most often aligned with the north and east directions correspondingly; the z-axis complete the right-hand coordinate system, thus positing down. Regarding, Body-fixed frame, which is usually marked with the subscript \{b\}. The frame origin is defined at the center of gravity (CG) of the airplane; as for the orientation of the frame it is defined as follow: assuming that the aircraft has a vertical plane of symmetry, then x-axis and z-axis axes lie in that plane of symmetry; x-axis points toward the direction of flight and z-axis points downward and y-axis points right, thus completing the right-hand system.

The state-space representation of the aircraft can be written in the following form:

\[ X(t) = f(X,U) \]  \hspace{1cm} (1)
\[ Y(t) = g(X,U) \]  \hspace{1cm} (2)

Where X(t) is the state vector, Y(t) the output vector and U(t) the input vector.

\[ X(t) = \left[ r, v_b, \theta, w \right]^T \]  \hspace{1cm} (3)
\[ U = [\delta_a, \delta_e, \delta_r, T]^T \]  \hspace{1cm} (4)

Where:

- \( r = [x, y, z]^T \) is the position vector of the aircraft center of gravity in the earth frame.
- \( V_b = [u, v, w]^T \) is the Velocity vector of the aircraft in the body frame.
- \( \theta = [\phi, \theta, \psi]^T \) is the Euler angles vector Roll, Pitch, and Yaw.
- \( W = [w_p, w_q, w_r]^T \) is the angular velocity in body coordinates, Roll rate, Pitch rate, and Yaw rate.
- \( \delta_a, \delta_e, \delta_r \) are the control surface angles, namely Aileron, Elevator, and Rudder angles.
- \( T \) represents the thrust or propulsive force.
- Subscript b denotes body frame and \( x^T \) denotes transpose of x.

In section II chapter 14 of [6] a complete overview of different coordinate frames used in UAV applications is introduced, and a set of 6 DOFs equations of motion which describes the kinematics and dynamics of an UAV, is presented.

Formally, we proceed by separating what belongs to aerodynamics and dynamics [7], into two sub-models, dynamic sub-model and aerodynamic sub-model, as shown in figure 1.
Within the aerodynamic sub-model, the aerodynamic coefficients related to aerodynamic forces (Cx, Cy, Cz) as well as the coefficients of the aerodynamic moments (CL, CM, CN) can be estimated [8]. Therefore, based on these coefficients, the aircraft flight dynamics was modeled. Indeed, the former sub-model allows to predict and quantify the movement of the aircraft by following the input data (control surface angle and thrust) as shown in equation (4).

\[ C_i(\alpha, w_q, \delta_e) \approx C_{i0} + \frac{\partial C_i}{\partial \alpha} \alpha + \frac{\partial C_i}{\partial w_q} w_q + \frac{\partial C_i}{\partial \delta_e} \delta_e \]  

Where:
- \( C_i \) denotes the considered force (Lift or Drag) or Moment
- \( \alpha \) is the angle of attack
- \( \delta_e \) is the elevator angle
- \( w_q \) is the pitch rate

Several methods are used to determine the aerodynamic parameters of an aircraft. These methods can be grouped into a small number of categories, which are flight tests, wind-tunnel tests [1], [2] and numerical methods.

In most instances, the latter category is used. It is the most affordable to all users and based mainly on resolving numerical equations. In essence, we have two approaches. The analytical approach [11], which is used in the conceptual phase and the approach based on resolving the equation of fluid dynamics, called computational fluid dynamics (CFD) [3] [4], which can be 2-D or 3-D.

4. CFD workflow

Computation Fluid Dynamics or CFD is a set of numerical tools for solving equations of fluid dynamics. Originally developed for aeronautical uses, but now pervades all disciplines including flow phenomena [12]. Chapter 14 of the book [13] presents a summary of the different approaches and softwares used in CFD.

In this paper, Fluid Flow module of Ansys software is used. Formally, a CFD process involves the following steps:
- The entry point of the CFD method is the geometry (3D-model), usually presented as a CAD file,
• The geometry is then incorporated into the center of an enclosure which is used to simulate the flow and configured according to the aircraft wingspan,
• A mesh is developed to obtain different levels of fine refinement and its convergence and precision are studied,
• The mesh is configured according to the different sections created in order to apply the appropriate boundary conditions,
• The flow parameters are set up (fluid properties, turbulence model, flow properties, …),
• Flow dynamics equations are resolved,
• Results are extracted.

The big hurdle in this process is the input; the 3D model of the aircraft. Nevertheless, many techniques exist to generate 3D model, such as laser scanning and photogrammetry which is considered in this paper.

5. Photogrammetry
Photogrammetry refers to the possibility of extracting the 3D shape of a surface from a collection of images satisfying the condition that at least two images taken from different angles correspond to each scene or surface part.

Formally, to reconstruct the 3D model of a surface several parameters need to be defined. Firstly, the light rays hitting each pixel of the image, referred to as interior orientation (IO) or calibration. Secondly, the space location of the optical center of each image, referred to as the external orientation (EO). Now, based on IO and EO, it is possible to make a 3D intersection between light rays of different images. Therefore, the intersection rays defines the location of the surface that reflected the light of the sensor, in this case the aircraft external surface. Repeated over the pixel of overlapped images, it becomes possible to reconstruct the 3D-shape of the aircraft, this step is called dense correlation.

In essence, the photogrammetry process involves the following steps [14]:

• Field preparation (targeting, camera setting…),
• Image acquisition,
• Detecting tie points between different images,
• Estimating interior and exterior orientations,
• Bundle adjustment
• Dense image matching to produce a dense 3D point cloud.

6. Methodology
The methodology presented in this paper, relays on three main steps (flowchart of figure 2). The first step, hinge on applying a photogrammetric process whereby we generate a dense point cloud of the aircraft was performed with MicMac software. With regards to the second step, we meshed the point cloud and adapted the geometry by smoothing the surfaces, deleting appendices not required for control stability study, and filled in all imperfections in the geometry such as holes. Once the geometry smoothed and fixed, we extracted it in order to create a CAD file. Several modules of 3D-reshaper software were used to mesh and extract the geometry then, SpaceCalim software was used to fix the geometry. As to the third step, the CAD model was imported as a solid file e.g. IGES format (Initial Graphics Exchange Specification) into Ansys Fluent and the workflow was applied as presented in section 4.
7. Results
We applied the methodology presented in the previous section, on Cessna 182 aircraft. Regarding the photogrammetry step, 312 images have been taken using Canon D750 camera with a 24 mm lens. In addition, 30 coded targets and 08 scale bars have been used in order to scale the 3D model and to determine the accuracy of the final model.

The results of the image alignment and dense correlation are summarized in the table 1 below.

| Table 1. Results of photogrammetry process phase |
|-----------------------------------------------|
| Aligned images | 302/312 |
| Re-projection error (pix) | 0.412 |
| Number of tie points | 345 143 |
| RMSE on the scale bars (mm) | 0.4 |
| Dense point cloud | 2 395 134 |
| Number of filtered points | 1 596 756 |
| Resolution (point/cm) | 1 |

Once dense point cloud was generated: Cloud and Mesh modules of 3D-Reshaper software have been used, in order to filter the point cloud and generate the mesh. After that, the geometry has been extracted and fixed in order to create the CAD model. Hereafter, the CAD model was therefore brought into Ansys Fluent and was meshed. However, for sake of simplicity and processing time optimization, we used only the wing of the aircraft because the largest lift and drag coefficients formation is deduced by the wing, as reported in many papers the wing has the largest proportion on lift and drag coefficients [15], [16], [17]. Figure 3 depicts the screen-shots of different results achieved after the two first steps of the methodology. Figure 4, shows the mesh which was carried out in this analysis.
Figure 3. Screen-shots of different results achieved after the two first steps of the methodology. The first image, on the left, represents the dense point cloud of the aircraft after filtering. The second image, in the middle, represents the aircraft after meshing and the last image, on the right, represents the CAD geometry model extracted from the mesh and fixed using SpaceClaim software.

Figure 4. Mesh generation around the wing for CFD analysis

Next, the flow parameters (fluid properties, turbulence model, flow properties, etc …) were set up and the flow resolution were performed during which various angles of attack were used. The results of the simulation are summarized in the table 2.

**Table 2. Angles of attack vs Lift coefficient and drag coefficient**

| $\alpha$ | 0  | 1.94 | 3.88 | 6.166 | 7.77 | 10  | 11.94 | 13.88 | 15.97 | 17.77 | 20  |
|----------|----|------|------|-------|------|-----|-------|-------|-------|-------|-----|
| $C_L$    | 0.1| 0.225| 0.377| 0.477 | 0.588| 0.722| 0.871 | 0.9866| 1.11  | 1.23  | 0.9 |
| $C_D$    | 0.0055| 0.0056| 0.016| 0.0277| 0.0388| 0.0555| 0.0722| 0.0972| 0.1194| 0.144 | 0.266 |

The graphs shown in Figure 5 show that the lift and drag increase first with the angle of attack and then, when the latter exceeds a value commonly known as the stall angle, the lift starts to decrease. This is the stall phenomenon. These results match the theoretical ones.
8. Conclusion
A methodology for the estimation of the aerodynamic coefficients of an aircraft has been presented in this paper. The photogrammetry workflow was used to obtain the aircraft 3D model. Based on this model, a Computational Fluid Dynamics (CFD) simulation using Ansys Fluent software was used in order to estimate the aerodynamic coefficients for different angles of attack. Finally, simulations were carried out and results were presented that match the theoretical ones.

A future work will focuses mainly on the validation of these results. The validation phase of the CFD calculation takes place in several stages, according to the guidelines of AIAA [18] and ASME [19]. Once the validation phase is complete, these results will be used to develop the aircraft flight controller.

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