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Aerodynamic Analysis and Wind Tunnel Testing of a MALE UAV

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Abstract.

This study investigates the aerodynamic characteristics of a Medium-Altitude, Long-Endurance (MALE) UAV by employing analytical/ semi-empirical, numerical, and empirical methods, with experimental validation through wind tunnel testing. The goal is to assess the accuracy and limitations of these in the aerodynamic analysis of similar UAV configurations. First, and due to the absence of critical geometric data. a 3D laser scanning technique is used to identify the complete geometric model of the studied UAV. Then, the developed geometric model together with the flight conditions are used to perform the aerodynamic analysis using a custom-developed analytical/ semi-empirical tool (AeroMech), the empirical DATCOM tool, and the numerical panel method implemented in XFLR5. To validate the results, a scaled model is designed and manufactured based on the identified geometry for wind tunnel testing. The experimental aerodynamic data are analyzed and compared with the data obtained from the diverse methods.

1 Introduction

Aerodynamic analysis is essential for understanding and predicting the performance of aircraft. A range of techniques, each with its own strengths and limitations, are employed to achieve this understanding. These techniques can be broadly categorized as analytical, empirical, semi-empirical, numerical, computational, and experimental. Analytical methods, often based on simplified assumptions, provide closed-form solutions to aerodynamic problems. While offering valuable theoretical insights, they are typically limited to simplified geometries and flow conditions [1, 2]. Empirical methods rely on experimental data and curve fitting to establish relationships between aerodynamic parameters. These methods can be useful for specific configurations but lack generality and may not accurately predict behavior outside the tested range [3]. Semi-empirical methods bridge the gap between analytical and empirical approaches, combining theoretical principles with empirical corrections. They offer a balance between accuracy and computational cost, making them suitable for preliminary design stages [4, 5, 6]. Numerical methods discretize the governing equations of fluid flow and solve them iteratively. These methods can handle complex geometries and flow conditions but require significant computational resources [7, 8, 9, 10]. Experimental techniques, primarily wind tunnel testing, provide real-world data on aerodynamic performance. While invaluable for validating computational models and exploring complex flow phenomena, they can be expensive and time-consuming. Each of these techniques plays a crucial role in aerodynamic analysis, and their selection depends on the specific objectives of the study, the desired level of accuracy, and the available resources. Typically, a combination of these methods can provide a comprehensive understanding of aircraft's aerodynamic characteristics [11, 12, 13].

Medium-altitude, long-endurance (MALE) unmanned aerial vehicles (UAVs) have become indispensable for modern aerospace and military operations due to their unique capabilities and cost-effectiveness. These platforms offer a compelling combination of extended endurance, medium-altitude operation, and the ability to carry a wide array of payloads, making them ideal for persistent surveillance, reconnaissance, and strike missions. The aerodynamic performance of MALE UAVs is a critical factor in their operational efficiency and mission success.

Digital DATCOM, an empirical method is a widely used tool for analyzing the aerodynamic characteristics of aircraft, including (UAVs). Several researchers have employed Digital DATCOM in their studies on UAV design and performance. Adil Loya et al. [14] used it to compare the aerodynamic characteristics of high-wing, mid-wing, and low-wing UAV configurations obtained from Computational Fluid Dynamics (CFD) simulations. Their study aimed to find the UAV configuration with the best aerodynamic efficiency. Bingyu Tan et al. [15] investigated the influence of asymmetric wing damage on the aerodynamic characteristics of a flying-wing UAV using it. They analyzed the effect of different damage conditions on the UAV's aerodynamic coefficients and static stability. Jing Huang et al. [16] utilized it to design the fixed-wing mode of a ducted-fan tiltrotor UAV. They calculated the stability and control derivatives of the UAV under different cruise speeds and angles of attack. Mukesh Raju et al. [17] compared the aerodynamic stability coefficients obtained from Digital DATCOM and XFLR5 software with CFD simulations for a UAV designed for agriculture and surveying applications. Their study demonstrated high accuracies between the two software programs and CFD results.

XFLR5 is a numerical technique used in the field of aerodynamics to analyze the performance of aircraft and UAVs. It is a powerful tool that allows researchers to simulate the behavior of aircraft and UAVs under different flight conditions, providing valuable insights into their stability and performance. Several researchers have used XFLR5 to study various aspects of UAV design and performance. Lesalli and Cahyono [18] investigated the longitudinal static stability of a flying wing UAV with varying wing sweep angles. They found that the UAV was stable for a range of sweep angles, demonstrating the capability of XFLR5 in assessing stability characteristics. Septiyana et al. [19] used it to analyze the aerodynamic characteristics of a twin-tail boom unmanned aircraft. Their study focused on predicting the lift and drag coefficients, providing valuable data for optimizing the aircraft's design. Firdaus et al. [20] conducted a numerical study to predict the aerodynamic performance of a UAV based on chord tip and offset of the wing. They used XFLR5 to simulate the UAV's performance and found that the chord tip and offset significantly influenced the lift and drag coefficients. Prasetyo et al. [21] analyzed the wing shape of a UAV using XFLR5 and DATCOM software. Their study aimed to determine the ideal wing model for the UAV. Antonio and Yan [22] used it to design and analyze the performance and stability of a fixed-wing UAV. They investigated different airfoil and tail configurations, demonstrating the software's capability in optimizing UAV design for specific requirements. Oladejo et al. [23] conducted an aerodynamic performance analysis of an optimized airfoil for UAVs using XFLR5. Their study compared the performance of the optimized airfoil with a reference airfoil, demonstrating the software's ability to assess and compare different airfoil designs. Prasetyo et al. [21] investigated different wing models for the STRIKE 50 UAV using Digital DATCOM and XFLR5 to optimize performance. Adeyi et al. [24] investigated the influence of airfoil geometry on the aerodynamics of a VTOL UAV at low Reynolds numbers using XFLR5. They analyzed different airfoils and found that NACA 6409 demonstrated superior performance, highlighting the software's capability in evaluating airfoil designs for specific flight conditions.

The analytical/empirical method AeroMech Tool has proven valuable in the field of UAV design and analysis. Magdy et al. [25] developed and verified AeroMech for rapid estimation of airplane aerodynamic characteristics during early design stages. The tool combines analytical and empirical approaches to expedite the calculation of aerodynamic characteristics with acceptable accuracy. The authors digitized and implemented numerous empirical relations and analytical-empirical equations into AeroMech, facilitating and speeding up the calculations. They selected Cessna-182 and Cessna-310 airplanes as case studies to verify AeroMech against Digital DATCOM, XFLR5, and published data. The results showed that AeroMech can predict aerodynamic characteristics with reasonable accuracy for preliminary design steps, saving time and resources in the early design stages.

These studies demonstrate the wide range of applications of Digital DATCOM, XFLR5, also AeroMech Tool in airplanes research specially UAV. The softwares ability to simulate various aspects of UAV design and performance makes them invaluable tools for aerodynamic analysis.

This study investigates the aerodynamic characteristics of a Medium-Altitude, Long-Endurance (MALE)

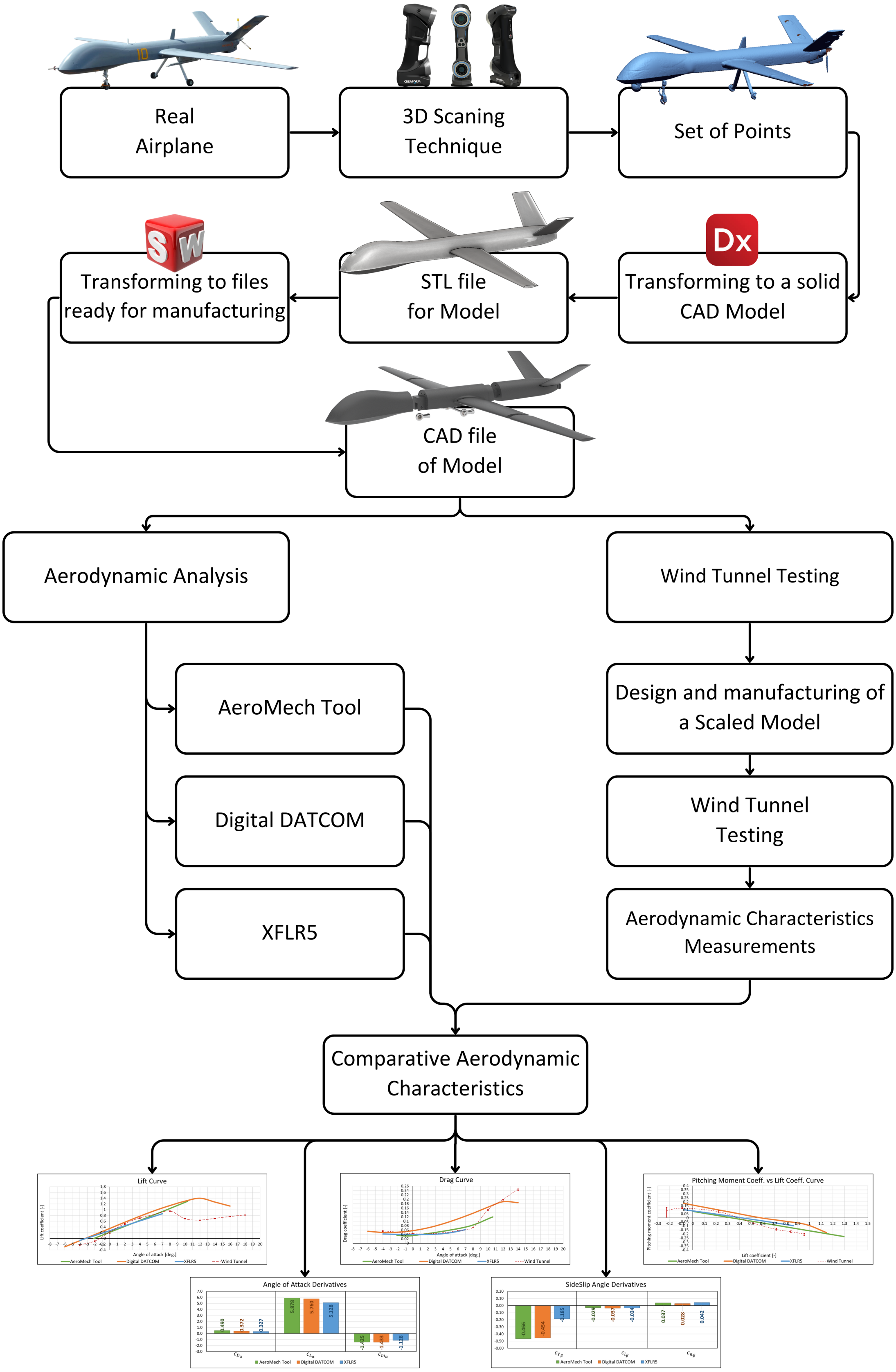

Figure 1. Workflow of the study

UAV. This investigation employs a multi-faceted approach, combining physical modeling, analytical, empirical, numerical analysis, and wind tunnel testing as illustrated in Figure 1. The process begins with the creation of a geometric model of the MALE UAV where a 3D scanning technique is used to capture the complex geometry of the UAV, generating a digital representation. This data is then processed to create a Computer-Aided Design (CAD) model, which served as the basis for manufacturing the scaled wind tunnel model. Following fabrication, wind tunnel testing is performed to acquire experimental aerodynamics. This data focused on key aerodynamic characteristics, including lift, drag, and pitching moment. The experimental data served as a benchmark for comparison with other methods. The experimental data was then analyzed and compared with results obtained from a range of aerodynamic analysis techniques. Semi-empirical methods were employed to provide initial performance estimates and a baseline for comparison. Numerical techniques were used to analyze the aerodynamic forces and moments acting on the UAV model, offering a balance between computational cost and accuracy. This comprehensive approach, combining experimental wind tunnel testing with various computational methods, facilitated a thorough evaluation of the aerodynamic characteristics of the MALE UAV model. By comparing experimental and computational results, this study aims to highlight the strengths and limitations of each method, contributing to a more nuanced understanding of their applicability in aerodynamic analysis and informing the selection of appropriate tools for future UAV design.

2 Case Study and Methodology

This part focuses on analyzing the aerodynamic performance of a specific MALE UAV using multiple methods. The UAV's specifications will be defined, followed by a comprehensive aerodynamic analysis using Digital DATCOM, XFLR5, and AeroMech Tool. The results from these three methods will be compared to understand their similarities and differences. Additionally, wind tunnel testing will be conducted to validate some of these results and assess the accuracy of the different methods. This multifaceted approach aims to provide a comprehensive understanding of this UAV's aerodynamic behavior.

2.1 Case Study

A prominent MALE UAV shown in Figure 2 is selected as a case study for this research. This study aims to contribute to the understanding of this MALE UAV's aerodynamic performance by utilizing various methods, including Digital DATCOM, XFLR5, the custom-developed AeroMech Tool [25], and wind tunnel testing. Analyzing this UAV allows for a deeper understanding of its aerodynamic behavior and the potential for exploring design improvements for future UAVs. This MALE UAV has a wingspan of 14 meters, a maximum takeoff weight of 1100 kg, and is powered by a 100 hp piston engine, allowing it to reach a maximum speed of 280 km/h with an endurance of 20 hours. Its ability to carry a payload of up to 200 kg makes it a versatile platform suitable for a wide range of missions. A summary of the important specifications of the case-study MALE UAV is presented in Table 1.

Figure 2. The case-study MALE UAV.

Table 1. The main Specifications of the case-study MALE UAV

Specification	**Value**
Wingspan	14 m
Length	9.05 m
Height	2.77 m
Maximum Take-off Weight	1,100 kg
Payload	200 kg
Maximum Speed	280 km/h
Endurance	20 hours
Service Ceiling	5,000 m

2.2 Aerodynamic Analysis using Multi-fidelity Tools

This part presents a comparative study of three different aerodynamic prediction methods applied to the MALE UAV real size and model. These methods, encompassing Digital DATCOM, XFLR5, and the AeroMech Tool, offer varying levels of fidelity and complexity. By comparing their predictions, this analysis aims to identify the strengths and weaknesses of each approach, ultimately guiding the selection of the most suitable method for analyzing the aerodynamic behavior of the MALE UAV.

Digital DATCOM, developed in the 1960s, is a foundational tool employed for aerodynamic analysis. The software utilizes an analytical-empirical approach, combining theoretical calculations with empirical data derived from extensive wind tunnel testing and flight data. This methodology enables efficient estimation of aerodynamic characteristics without the computational demands of complex numerical simulations. This efficiency proves particularly valuable in preliminary design stages where rapid iterations and trade-off studies are essential. A key strength of Digital DATCOM is its speed in providing quick estimations of aerodynamic characteristics. Additionally, the software can estimate static stability derivatives. We utilized Digital DATCOM's specific input file format, using namelists to organize the data. These namelists are designated blocks of data that begin and end with a dollar sign ($). Each namelist serves a specific purpose in defining the aircraft's characteristics. The key namelists we used are: $FLTCON, which defines the flight conditions such as altitude, velocity, and Mach number for the aerodynamic analysis, $\$SYNTHS$, which specifies the locations of aircraft components like the wing, tail surfaces, and fuselage relative to a reference point, $\$BODY$, which defines the fuselage geometry including its length, diameter, and cross-sectional shape, $\$WGPLNF$, which defines the wing planform geometry including its span, root chord, tip chord, sweep angle, and dihedral angle, $\$HTPLNF$, which defines the horizontal tail planform geometry including its span, root chord, tip chord, sweep angle, and dihedral angle, and $\$VTPLNF$, which defines the vertical tail planform geometry including its span, root chord, tip chord, sweep angle, and dihedral angle. The solution sequences in Digital DATCOM involve a series of calculations performed by the software to estimate the aerodynamic characteristics of the UAV. The program estimates different characteristics such as lift, drag, pitching moment, rolling moment, and yawing moment. The solution sequences begin with the user inputting the geometry, including wing planform, fuselage geometry, and control surface deflections. The program then calculates the corresponding aerodynamic derivatives, which are essential inputs to the stability and control analysis of the UAV. The accuracy of the Digital DATCOM program depends on the accuracy of the input geometry and the limitations of the program itself.

The XFLR5 solution sequence begins with the creation of a three-dimensional digital model of the airplane's geometry. This is done using a CAD tool within the program to create a solid model of the fuselage, wings, tail, and other components. The next step is to divide the geometry into small computational sections, each with a specific shape and orientation. These sections, called "panels," represent the UAV geometry. After the panels have been defined, XFLR5 predicts the aerodynamic forces acting on the UAV, including lift, drag, and pitching moment. The results of the calculation are then analyzed to determine the airplane's key aerodynamic characteristics, including its maximum lift, drag, pitching moment coefficients, and stability derivatives.

The AeroMech Tool solution sequence involves several steps to predict aerodynamic characteristics. Initially, the process involves evaluating lift characteristics by determining the zero-lift angle of attack, calculating the lift curve slope, identifying the linear range of the angle of attack, and ascertaining the angle of attack that yields maximum lift, leading to the construction of the wing lift curve. The next step focuses on evaluating the pitching moment characteristics, starting with determining the zero-lift pitching moment coefficient, followed by calculating the slope of the pitching moment curve, and finally constructing the wing pitching moment curve. The subsequent step involves evaluating drag by decomposing its sources into specific components, such as wing drag, empennage drag, fuselage drag, nacelle drag, and interference drag, each calculated using a blend of analytical methods and empirical data to estimate the total drag. The final step involves calculating stability derivatives. This comprehensive aerodynamic analysis of our MALE UAV.

This analysis involves a comprehensive comparison of the aerodynamic characteristics and derivatives of a MALE UAV predicted by these three methods. The comparison encompasses various aspects, including the lift curve, drag curve, pitching moment curve, and polar curve. Additionally, the analysis delves into the comparison of aerodynamic derivatives, such as angle of attack derivatives, sideslip angle derivatives, pitch rate derivatives, roll rate derivatives, and yaw rate derivatives, to evaluate the strengths and weaknesses of each method in capturing the stability characteristics of the MALE UAV. This comprehensive comparison provides valuable insights into the accuracy and reliability of different aerodynamic prediction methods, aiding in the selection of appropriate tools for analyzing the aerodynamic behavior of MALE UAVs and informing potential design improvements. Figures 3 to 12 compare these results of three aerodynamic analysis methods (AeroMech, Digital DATCOM, and XFLR5) of our MALE UAV.

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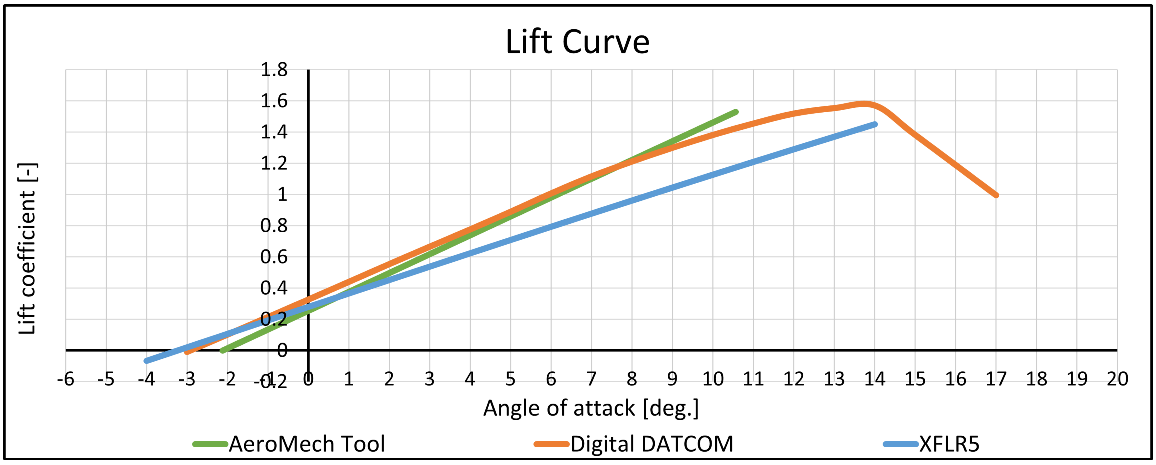

Figure 3. Comparison of lift curve of the MALE UAV

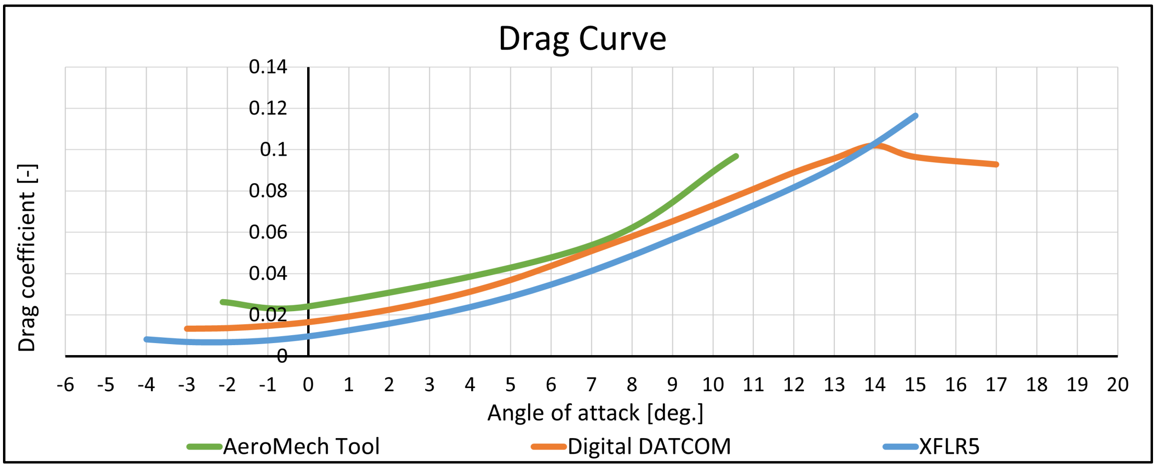

Figure 4. Comparison of drag curve of the MALE UAV

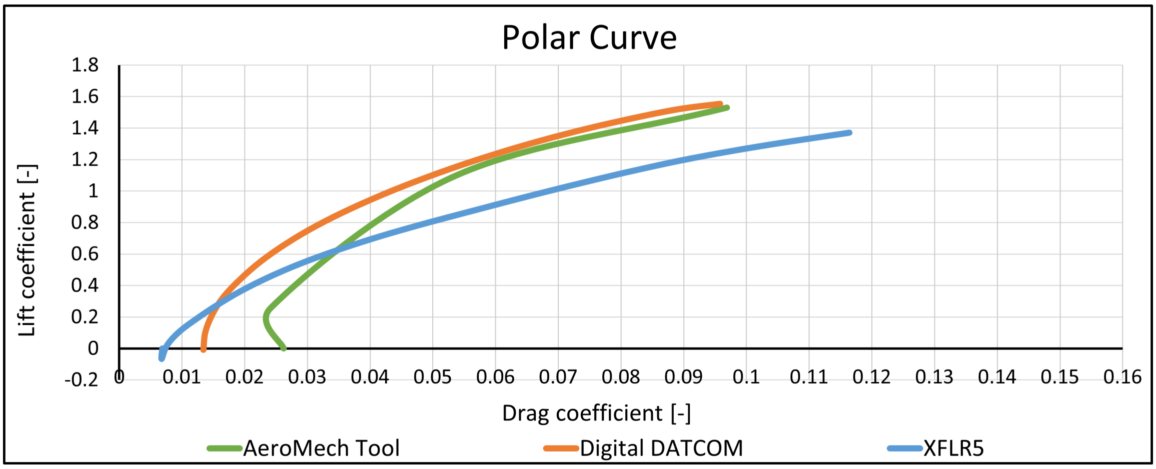

Figure 5. Comparison of polar curve of the MALE UAV

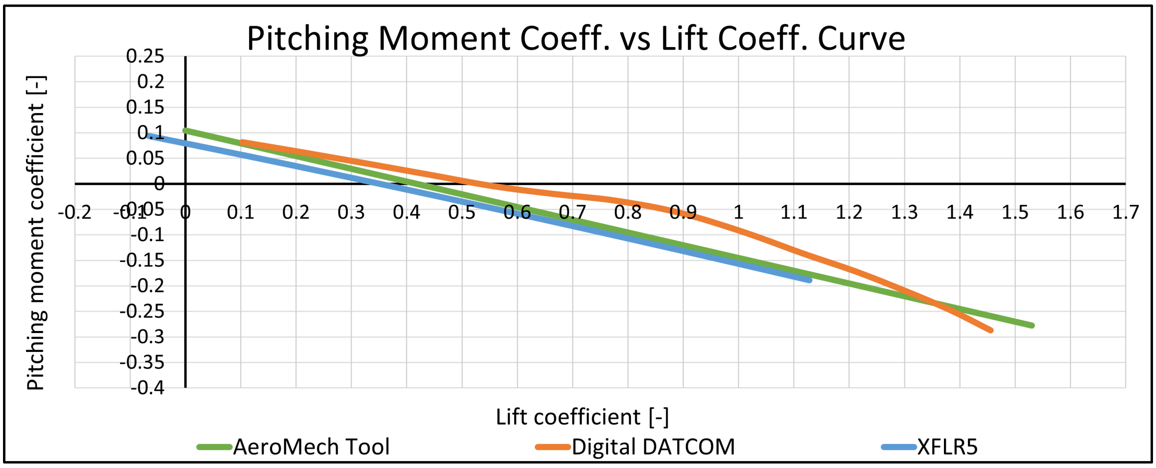

Figure 6. Comparison of pitching moment curve (C_m-C_L) of the MALE UAV

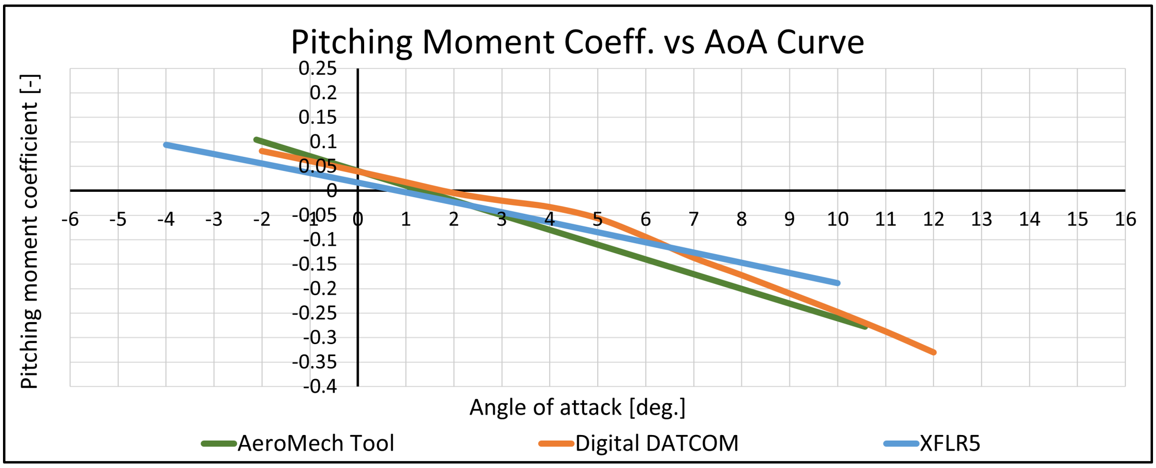

Figure 7. Comparison of pitching moment curve (C_m-α) of the MALE UAV

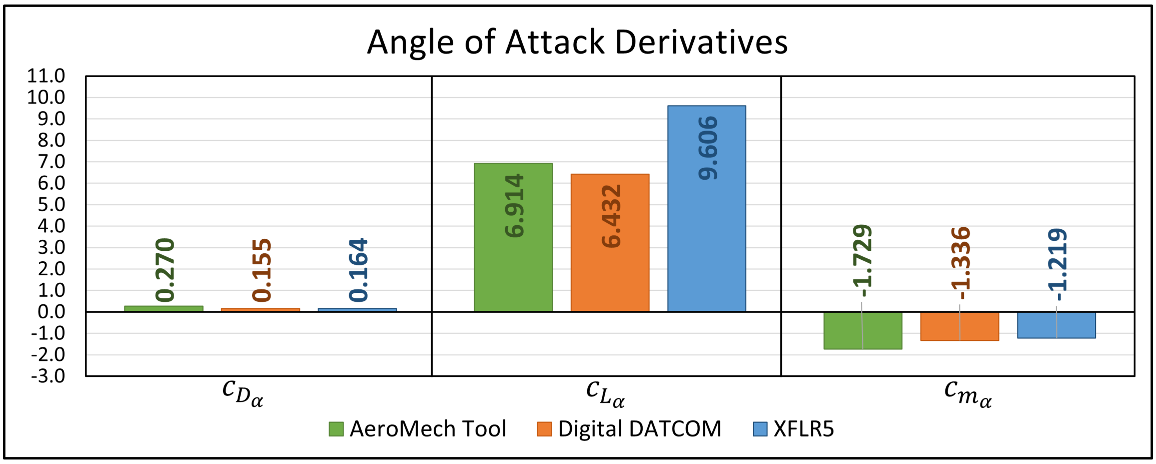

Figure 8. Angle of attack derivatives of the MALE UAV

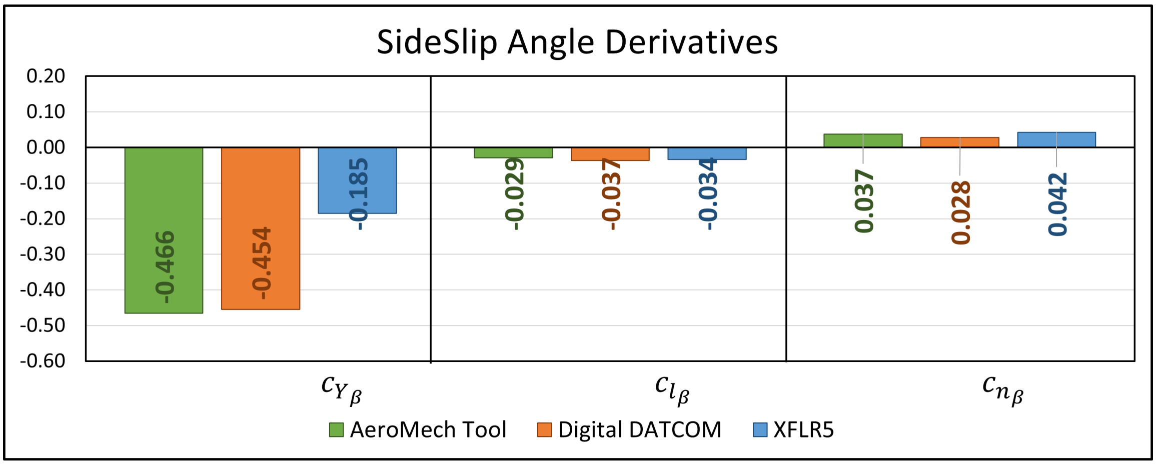

Figure 9. Sideslip angle derivatives of the MALE UAV

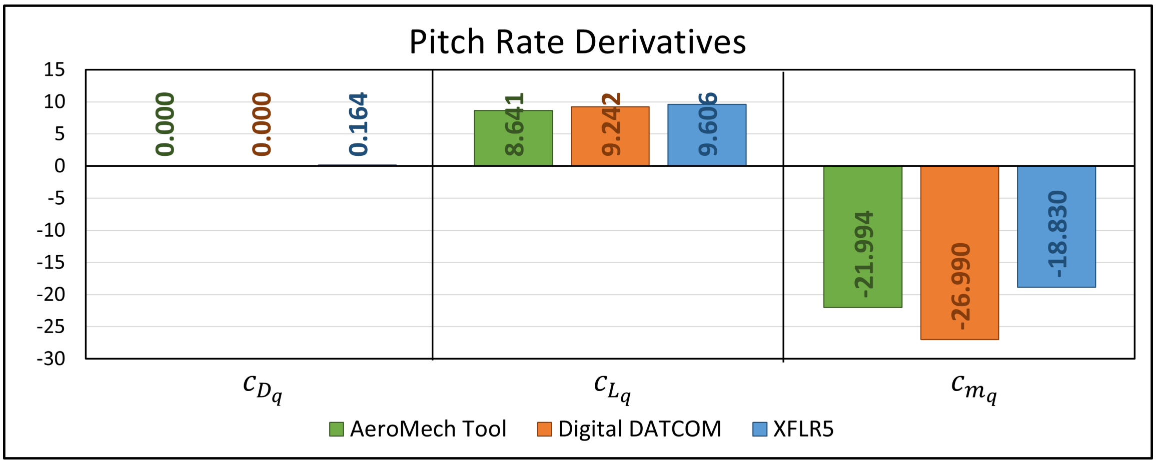

Figure 10. Pitch rate derivatives of the MALE UAV

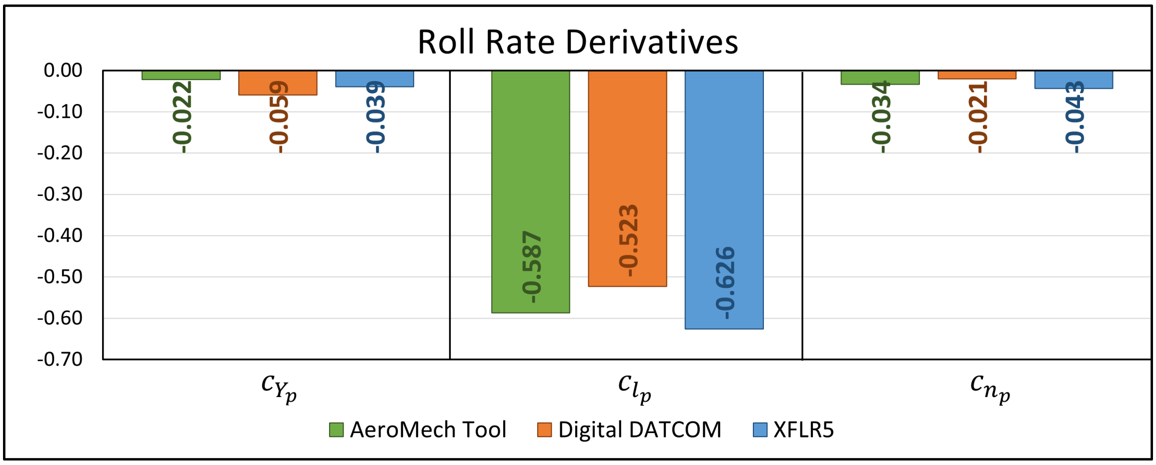

Figure 11. Roll rate derivatives of the MALE UAV

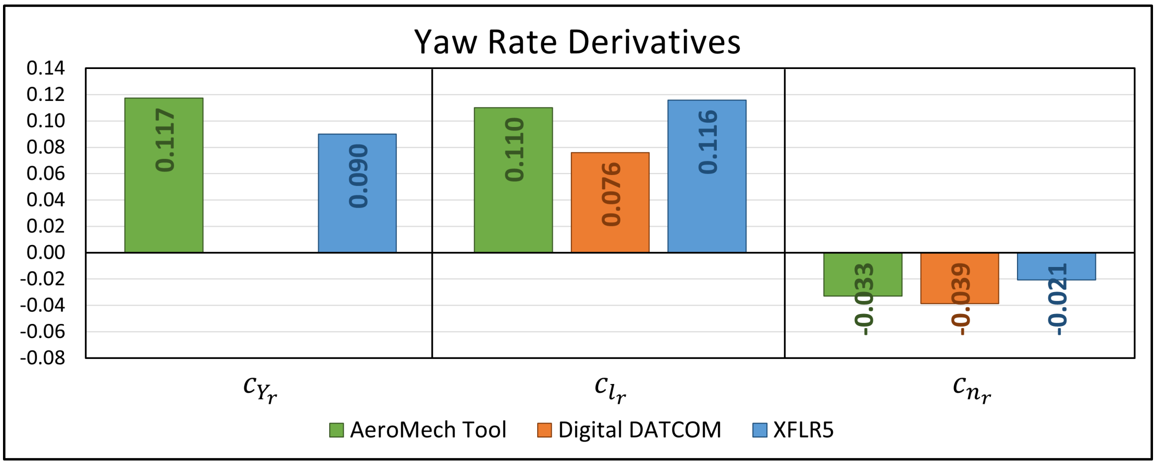

Figure 12. Yaw rate derivatives of the MALE UAV

3 Experimental Setup

This section details the process of conducting a wind tunnel experiment to analyze the aerodynamic characteristics of this MALE UAV model. This involves design and manufacturing of a scaled model, using a low-speed wind tunnel, installing the model with a sting balance, and employing a data acquisition system to measure forces and moments. The data was then processed to isolate aerodynamic forces, correct for balance offset, and transform the data into a wind-fixed coordinate system for analysis.

3.1 Design and Fabrication of the scaled wind tunnel Model

This part details the transformation from digital design to physical model of this MALE UAV, a crucial step for wind tunnel testing. The process starts with capturing the UAV complex geometry using 3D scanning. A Creaform Handyscan 700, known for its precision and portability, created a detailed point cloud representation of the entire UAV, effectively capturing its subtle curves and contours. This raw point cloud data, while visually rich, aren't directly usable in CAD software. Therefore, we utilized Geomagic Design X, a reverse engineering software, to transform the point cloud into a solid CAD model. This involved noise reduction, feature identification, and the creation of a refined 3D mesh, ultimately resulting in a CAD model ready for analysis and modification.

This digital model is then imported into SolidWorks for further refinement. This process involved subtle adjustments to ensure both aerodynamic fidelity and experimental feasibility as shown in Figure 13. With the digital model finalized, we turned our attention to manufacturing. While traditional methods like CNC machining, casting, and injection molding are existed, 3D printing emerged as the ideal solution. Its additive nature allows for the creation of complex geometries with minimal material waste and high precision, offering a cost-effective and rapid prototyping pathway.

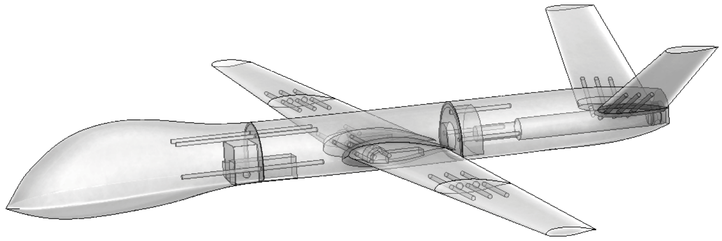

Figure 13. Designed scaled wind tunnel model for 3D-Printing.

After evaluating various 3D printing materials like ABS, PLA, PETG, and nylon, PLA is seleted for its ease of printing, dimensional stability, and ability to produce smooth surface finishes, all vital for accurate aerodynamic measurements. Finally, the printed components underwent post-fabrication processing. This included support removal, cleaning, surface refinement through sanding and filling, and careful assembly using internal structural elements and adhesives. A primer and paint finish completed the process, resulting in a high-quality 3D printed model ready for wind tunnel testing.

3.2 Introduction to The MTC Low Speed Wind Tunnel

The MTC low-speed wind tunnel is a versatile, single-return, closed-circuit, e experimental facility designed for aerodynamic research and testing. Its specifications, including test section dimensions and key aerodynamic characteristics, are detailed in Table 2. Capable of operating with both closed and open test sections, it allows for the study of a wide range of aerodynamic phenomena and model configurations. The tunnel emphasizes flow quality, with low turbulence and a uniform velocity distribution across the test section. A sensitive aerodynamic balance system enables precise measurement of forces and moments on test models. The tunnel rectangular test section, shown in Figure 14, has a 7:10 height-to-width ratio with a turntable for model rotation, and flat side walls for mounting specialized models. Downstream, the exit cone ensures a smooth airflow transition to the diffuser, maintaining constant static pressure and reducing pulsations. The small and large diffusers to prevent flow separation, gradually decelerate the airflow, converting kinetic energy into pressure energy. Four corners, each with turning vanes, guide the airflow smoothly, minimizing drag. A wire mesh safety screen between the first and second corners protects the fan. The smoothing chamber, between the fourth corner and the entrance cone, houses flow straighteners and turbulence screens to eliminate swirl and ensure uniform airflow. Finally, the entrance cone (nozzle) accelerates the airflow into the test section.

Table 2. MTC Low-Speed Wind Tunnel Specifications

Characteristic	Value
Maximum follow velocity	56 m/s
Test section Width	1.50 m
Test section Height	1.15 m
Test section length	3.00 m
Section Area	1.6 m^2

3.3 Model Installation and Sting Balance Setup

The scaled model of the MALE UAV is directly mounted within the wind tunnel's test section as shown in Figure 15. This direct mounting approach minimizes potential interference effects and allows for a more streamlined setup. The model is securely attached to a sting balance, which is connected to the wind tunnel's support system at the trailing edge of the model in the longitudinal axis.

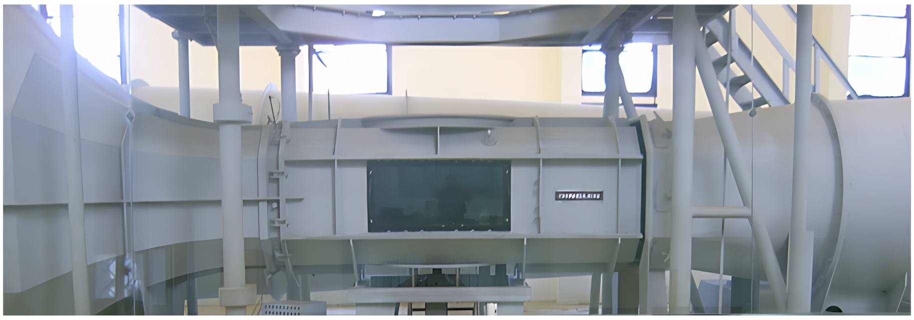

Figure 14. Test Section of MTC Low-Speed Wind Tunnel

Figure 15. The MALE UAV Model in MTC Low-speed Wind Tunnel Perspective View.

The wind tunnel experiments utilized a comprehensive software interface shown in Figure 16. It allowed for the observation of critical parameters such as airspeed, fan RPM, air temperature and humidity, static and barometric pressure, air density, and all six force and moment components. The software also controlled wind tunnel operations, including fan speed regulation, target airspeed setting, and model angle of attack and sideslip adjustments.

The Aerolab 6-component Internal Strain Gage Force/Moment Balance is employed to measure aerodynamic forces and moments on the model. This highly sensitive instrument, is a solid stainless steel rod designed to be mounted between the model and a positioning system. The balance, 11 inches in length and 1 inch in diameter.

3.4 Test Conditions and Data Acquisition

This part outlines the specific conditions under which the wind tunnel tests are conducted and the data acquisition procedures employed to ensure the accuracy and reliability of the experimental results. The wind tunnel tests are conducted at a freestream velocity of **30 m/s**, consistent with standard sea level atmospheric conditions. The aerodynamic performance of the model is systematically evaluated across a range of angles of attack, from **-8° to 16°**, with an increment of **2°** between each measurement. This range encompasses the typical flight envelope of the UAV, including stall and post-stall behavior, enabling the capture of critical aerodynamic phenomena such as flow separation and changes in lift and drag characteristics. At each angle of attack, the data acquisition system recorded the forces and moments measured by the sting balance for a specified duration. To enhance the reliability of the measurements and minimize the influence of random fluctuations, each measurement is repeated three times.

3.5 Data Post-Processing

This part describes the post-processing techniques applied to the raw wind tunnel data to extract accurate and meaningful aerodynamic information. This process involves separating the aerodynamic forces from

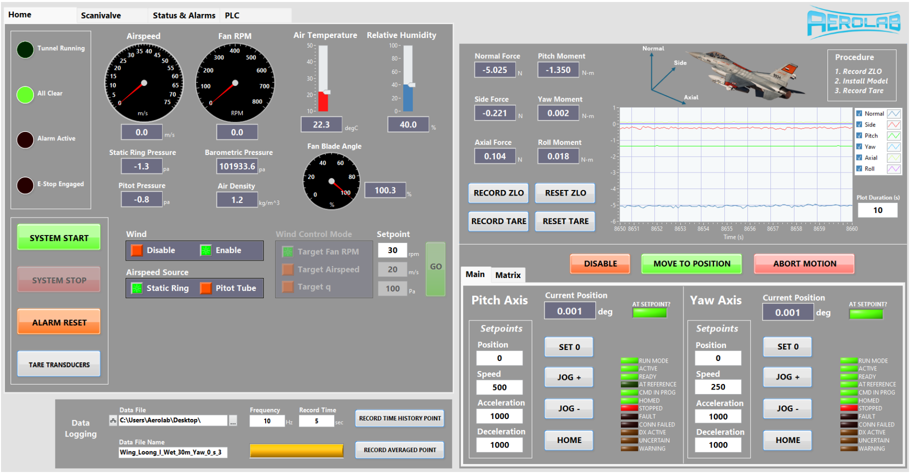

Figure 16. MTC Low-Speed Wind Tunnel Software User Interface.

inertial effects, correcting for the offset between the sting balance measurement point and the model's center of gravity, and finally transforming the data to the wind-fixed coordinate system.

3.5.1 Separation of Aerodynamic and Inertia Forces To isolate the pure aerodynamic forces acting on the model, a series of "dry" and "wet" tests are conducted. These tests aimed to separate the aerodynamic forces from the inertial forces and account for any interference effects from the sting balance and mounting system itself. The **dry tests** are performed with the wind tunnel turned off, eliminating any airflow and thus any aerodynamic forces. The **wet tests** are performed with the wind tunnel operating at the desired freestream velocity, generating aerodynamic forces on the model. Each dry and wet test is repeated three times at each angle of attack to ensure repeatability and minimize the influence of random errors. To obtain the pure aerodynamic forces acting on the model, a specific data reduction procedure is followed. First, the values of the forces and moments from the three repetitions of each dry test are calculated. Next, the values of the forces and moments from the three repetitions of each wet test are calculated. Finally, the inertial forces of the model and sting balance (from the dry tests) are subtracted from the values of the wet tests. This yielded the pure aerodynamic forces acting on the model.

3.5.2 Sting Balance Offset Correction The sting balance, used to measure the forces and moments acting on the model, is positioned at a slight offset from the model's center of gravity along the longitudinal axis (x-axis). This offset, if not accounted for, could lead to inaccuracies in the calculated aerodynamic moments. To address this, a correction is implemented to account for the offset between the sting balance measurement point and the model's center of gravity. This correction involved calculating the additional moments induced by the forces acting at the offset distance. Considering an offset distance 'A' along the longitudinal axis (x-axis of the body frame), the induced moment changes are calculated as:

$$\begin{aligned} \Delta M_x &= 0 \\ \Delta M_y &= F_z * A \\ \Delta M_z &= -F_y * A \end{aligned} \tag{1}$$

These corrections are then applied to the measured moments in the body frame:

$$\begin{aligned} M_{x_{\text{corrected}}} &= M_{x_{\text{measured}}} + \Delta M_x \\ M_{y_{\text{corrected}}} &= M_{y_{\text{measured}}} + \Delta M_y \\ M_{z_{\text{correceded}}} &= M_{z_{\text{measured}}} + \Delta M_z \end{aligned} \tag{2}$$

By considering this offset and applying the necessary correction, the moments are accurately transferred to the model's center of gravity. This ensured that the calculated moments truly reflected the aerodynamic loads experienced by the airplane during flight. This correction is essential for obtaining a representative depiction of the aerodynamic moments and ensuring the validity of the subsequent analysis.

3.5.3 Body-to-Wind Axes Transformation The forces and moments measured by the sting balance are initially referenced to the sting balance's coordinate system, also known as the body axes. However, for proper aerodynamic analysis, these measurements need to be transformed into the wind axes system. This transformation is crucial because it accounts for the relative orientation between the model and the freestream flow, ensuring that the aerodynamic forces and moments are expressed in a coordinate system aligned with the oncoming airflow. This transformation is achieved through a series of rotations, accounting for the angle of attack (α) and angle of sideslip (β). The rotation matrix is defined as follows:

$$A_{WB} = \begin{bmatrix} \cos\beta\cos\alpha & -\sin\beta & \cos\beta\sin\alpha \\ \sin\beta\cos\alpha & \cos\beta & \sin\beta\sin\alpha \\ -\sin\alpha & 0 & \cos\alpha \end{bmatrix} \tag{3}$$

This alignment with the wind axes system is essential for understanding the aerodynamic phenomena. By expressing the forces and moments in this system, the lift, drag, and side force components, as well as the rolling, pitching, and yawing moments can be directly extracted, providing a clearer picture of the aerodynamic forces and moments acting on the model.

4 Results and Discussion

The analysis focused on comparing the lift, drag, and pitching moment curves generated by each method between the full-scale and model-scale of the UAV shown in Figures 17 to 20 to assess their accuracy and identify any discrepancies as follows: There are some small disparities between the aerodynamic characteristics of the full-scale and model-scale, these disparities are primarily attributable to the variation in Reynolds numbers. All four methods showed good agreement in predicting **lift** coefficients at low to moderate angles of attack. This indicates that three methods are reliable tools for analyzing the lift within this regime. However, as the angle of attack increased, differences emerged, particularly near the stall point. The experimental data from wind tunnel testing showed an earlier stall compared to most predictions. Also the decrease in Reynolds number generally precipitates a reduction in the maximum lift coefficient C_L, as observed in the model's consistently lower C_L across all methods and wind tunnel tests at equivalent angles of attack. This reduction stems from earlier boundary layer separation, resulting from a thicker laminar boundary layer, and a consequential decrease in effective wing area. The **drag** curves generated by XFLR5, and AeroMech Tool were in close agreement. At the wind tunnel, the model exhibited a higher drag coefficient C_D, corroborating the anticipated increase in drag due to the proportionally larger laminar flow region and heightened susceptibility to boundary layer separation at lower Reynolds numbers. This separation, while potentially yielding lower skin friction in limited instances, ultimately elevates pressure drag. The **pitching moment** curves provided valuable insights into the wing's stability characteristics. All methods predicted an agreement at low to moderate angles of attack, but some divergence occurred at higher angles where flow separation effects became significant. Additionally, the model displayed a more negative pitching moment coefficient C_m, indicating an increased tendency for nose-down pitching, which is consistent with the altered pressure distribution over the aerodynamic surfaces induced by the reduced Reynolds number.

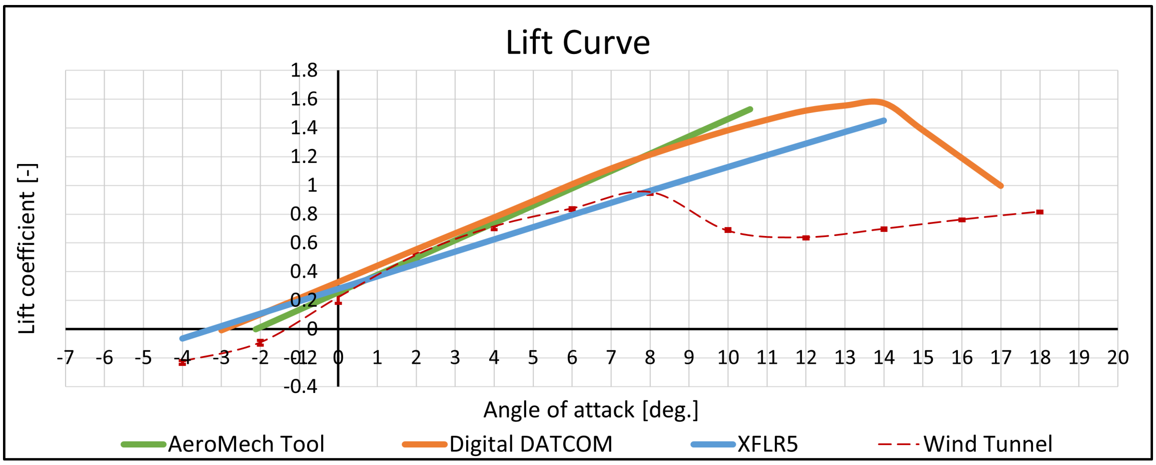

Figure 17. Comparison of lift curve of the MALE UAV full-scale and model-scale

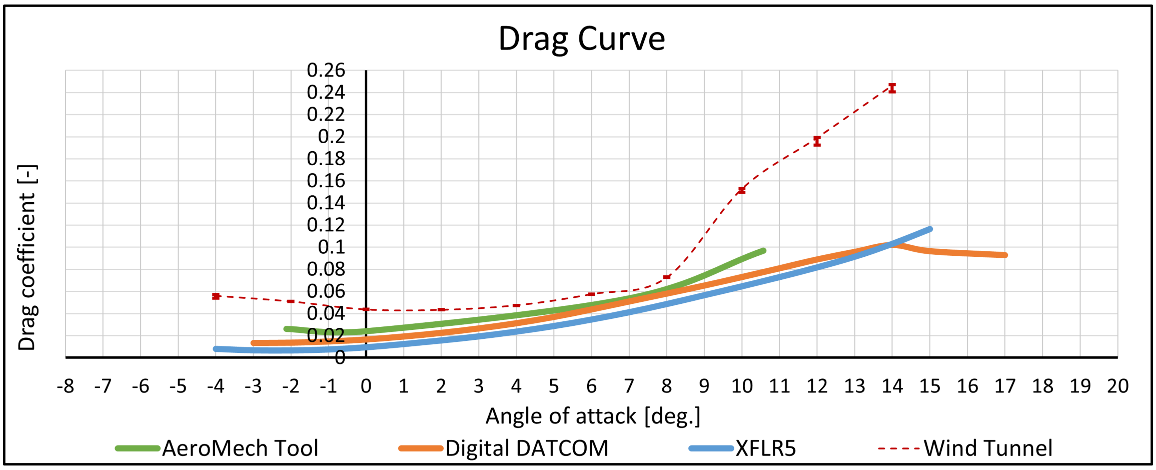

Figure 18. Comparison of drag curve of the MALE UAV full-scale and model-scale

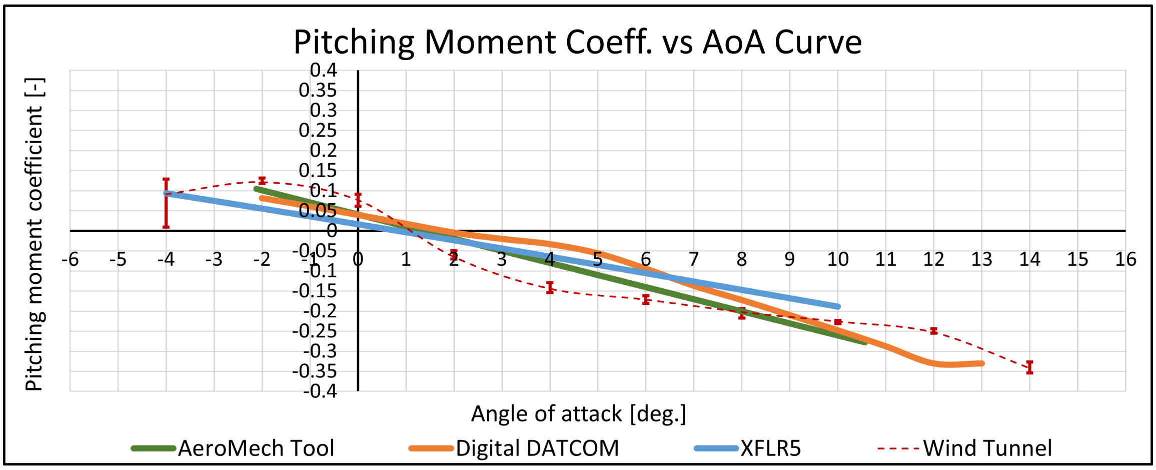

Figure 19. Comparison of pitching moment curve (C_m-C_L) of the MALE UAV full-scale and model-scale

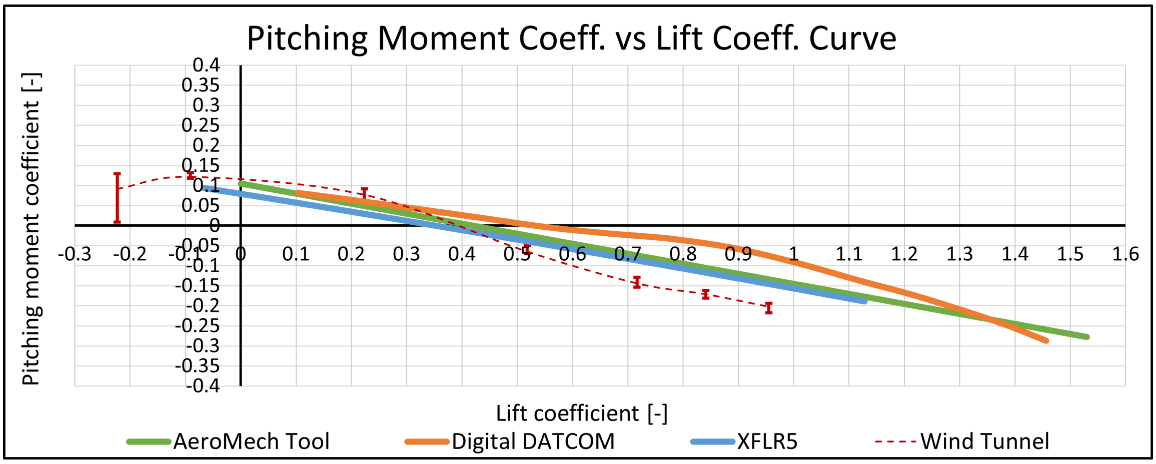

Figure 20. Comparison of pitching moment curve (C_m-α) of the MALE UAV full-scale and model-scale

5 conclusion and Future work

This study conducted an aerodynamic analysis of a MALE UAV at both full-scale and model-scale. For the full-scale UAV, three methods (AeroMech Tool, Digital DATCOM, and XFLR5) were employed to predict lift, drag, pitching moment curves, and aerodynamic derivatives. The model-scale analysis utilized wind tunnel testing for lift, drag, and pitching moment measurements. We make a comparison between the model-scale and full-scale results. Also this study makes several contributions as following: **First**, it employs a methodological approach by integrating physical modeling, wind tunnel testing, and some analysis tools, including semi-empirical and numerical methods. This multifaceted approach evaluates the aerodynamic characteristics of MALE UAVs and enables a deeper understanding of UAV performance. **Second**, the study validates various methods by comparing them with experimental wind tunnel data. This validation process offers valuable insights into the accuracy and limitations of each method, guiding researchers in selecting the most appropriate tools for different stages of UAV design and analysis. **Finally**, the findings of this study have direct practical implications for researchers and UAV designers to make informed decisions regarding design improving.

To address in the future the discrepancies observed between the calculated and measured aerodynamic derivatives, we will conduct wind tunnel testing of the model that will focus on obtaining measurements of some of the aerodynamic derivatives through free oscillation techniques. By perturbing the model and allowing it to oscillate freely in pitch, we will capture the natural frequencies and damping characteristics of the system. Analyzing these responses will allow us to extract some of the aerodynamic derivatives and see insights into the dynamic stability of the UAV. The acquired experimental data will then be compared with the predicted results from different tools presented in this study. This comparison will allow us to assess the accuracy and reliability of the different tools.

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