LA-8 Computational Analysis and Validation Studies Using FlightStream

Steven Geuther* and Xiaofan Fei†
NASA Langley Research Center, Hampton, Virginia, 23681

With the emerging market of Urban Air Mobility and the associated unique new flight vehicles with the capability of vertical takeoff and landing, design tools need to be calibrated to assist in the development of these new flight vehicle concepts. Distributed electric propulsion (DEP) covers these vehicles with high-energy flow from the array of motors, which leads to extensive propulsion/airframe interaction effects. With limited experimental data of vehicles using DEP and vehicle operation across a large range of angles of attack, including post-stall conditions, there is a lack of validated design tools to advance new vehicle concepts that have blown wings and operate in multiple flight modes. Although some CFD tools can handle the integration of multiple propulsors and unique geometries, the computational time with a full vehicle is extraordinary. FlightStream, a surface vorticity flow solver that can run in a fraction of the time of other CFD methods, has been evaluated using the Langley Aerodrome No. 8 (LA-8) vehicle as a test case. The LA-8 vehicle is a DEP tandem tilt-wing research vehicle that was designed, built, and tested at NASA Langley Research Center. The LA-8 design features both high-performance and high-technical risks aspects. The vehicle has gone through extensive design of experiments wind tunnel testing in the NASA Langley 12-Foot Low-Speed Wind Tunnel in order to capture all modes of operation. In addition, the LA-8 vehicle has undergone wind tunnel testing with and without propellers, which contributes to the validation of FlightStream for aerodynamic performance in blown and unblown wing cases. This study shows that FlightStream can produce trends and magnitudes of the lift and drag coefficients similar to the data collected from the wind tunnel testing of LA-8. The test cases were both blown and unblown wing cases and with and without high lift control surface deflections.

I. Nomenclature

C_D = Drag Coefficient
C_L = Lift Coefficient
Q = Free-stream Dynamic Pressure, lb/ft^2

II. Introduction

Urban Air Mobility (UAM) has fully embraced the design of novel vehicle concepts to attempt to satisfy the market of on-demand point-to-point operations. Numerous companies[§] as well as NASA [1] have released a vast amount of aircraft designs. Although each design is different, they all embrace having unconventional configurations compared to traditional aircraft. Without the appropriate validation of these concepts, the question remains if they can satisfy the mission requirements [2]. It is evident that there lacks a tool chain to predict the system level performance of these new configurations without significant computational time. In order to develop an adequate tool chain, new and old tools need to be validated for the additional vehicle configurations with propeller-airframe interactions, high incidence angle components and other features that need to be modeled. Previous research performed in the 1950's and 1960s with unconventional vehicle configurations, which provides an initial data set for tool development and validation [3] [4]. However, these aircraft did not adapt the use of electrification of the aircraft and distributed electric propulsion (DEP)

*Aerospace Engineer, Aeronautics Systems Engineering Branch, MS 238.
†Aerospace Engineer, Aeronautics Systems Analysis Branch, MS 442.
§A list of eVTOL aircraft concepts can be found: https://evtol.news/aircraft

and are not truly representative of the new configurations.

The Langley Aerodrome No.8 (LA-8), a tandem tilt-wing UAS, seen in Fig. 1, was built to understand a large subset of these complex interactions, like propeller-airframe and propeller-propeller interactions at a variety of wing incidence angles [5]. The LA-8 has undergone extensive wind tunnel testing in order to better understand the complex interactions between propellers and the airframe [6] [7]. Developing a tool chain that predicts the performance of the LA-8 would allow other vehicle configurations to be investigated with a certain level of confidence. This paper investigates the use of FlightStream to accurately model the propeller-airframe interactions as well as a configuration with and without control surface deflections. This paper will further discuss the validation studies that have already been completed on different complex models using FlightStream in Section III. The model and wind tunnel approach will be explained in Sections IV and V. The comparison of each case to the wind tunnel data will be provided in Section VI. Finally, an assessment of FlightStream in analyzing the LA-8 will be discussed in Section VII.

Fig. 1 Isometric view of the LA-8 in the NASA Langley 12-Foot Low-Speed Wind Tunnel.

III. FlightStream Background

FlightStream, an analysis tool developed by Research in Flight, is a surface vorticity flow solver with the capability to perform aerodynamic analyses on multi-element and unconventional vehicle designs [8]. FlightStream is known for its quick computational time, compared to CFD, with the added benefit of being able to model at a higher fidelity than traditional vortex lattice tools for conceptual design. FlightStream can accommodate both simplified models, e.g. Open VSP models, and detailed models, e.g. PTC Creo computer-aided design (CAD) models. Additionally, FlightStream has the ability to predict at and post stall, which is valuable for these new configurations that operate in transition with separated flow [8].

Previous FlightStream results indicate the capability of matching results of geometries like the NASA X-57 Maxwell, compared to CFD results, and the XC-142, compared to experimental data with only slight over-prediction [8] [9]. Additionally, high-lift devices like multi-piece flaps have been investigated and indicated promising results [10]. However, both of these papers investigated DEP and high-lift device separately. Vehicles intended for Urban Air Mobility operations will be using a combination of distributed electric propulsion and high-lift devices to achieve vertical takeoff and landing (VTOL) flight and the use of FlightStream should be validated as a suitable tool for vehicle design while examining both features at the same time. Examining FlightStream with the feature combinations will build up the validity of analysis tools to design future iterations of UAM vehicles with confidence.

Recent developments in FlightStream added functionality of surface proximity determination to prevent surfaces with small gaps between components, like between a control surface and a wing, from causing numerical instability.

This added functionality was heavily utilized for this study. The surface proximity addition allows for the user to select geometry components to do a proximity check to other components in order to nullify the instability created from the components with large mesh panels being too close to another surface. The version of FlightStream used for Section VI is 2020.2 - build 11152020.

IV. LA-8 CAD Model

For this study, the CAD geometry, seen in Fig. 2, was used in FlightStream. This CAD geometry was created for the development of the physical LA-8 wind tunnel and flight test model. Therefore, the CAD model that was used was not optimized for performing aerodynamic analysis, but rather for being built with 3D printing methods [11]. Additional modifications to the CAD model were required prior to meshing the geometry and running the analysis. The CAD model, as a function of being able to manufacture through 3D printing, was split into many smaller components and occasionally had gaps between each component to allow for servo actuators, wing spars, and clearance for the component to rotate. Other components that did not require the separation could be united. Therefore, the FlightStream model has gaps between certain components, but a continuous surface for other components. This is different compared to what is typically used for a traditional analysis (a single solid model). Additionally, as a requirement for manufacturing through 3D printing, each component required a thickness to safely manufacture, including the trailing edge, which was created to have a blunt edge. Modifications to the trailing edge were performed in FlightStream to sharpen each trailing edge.

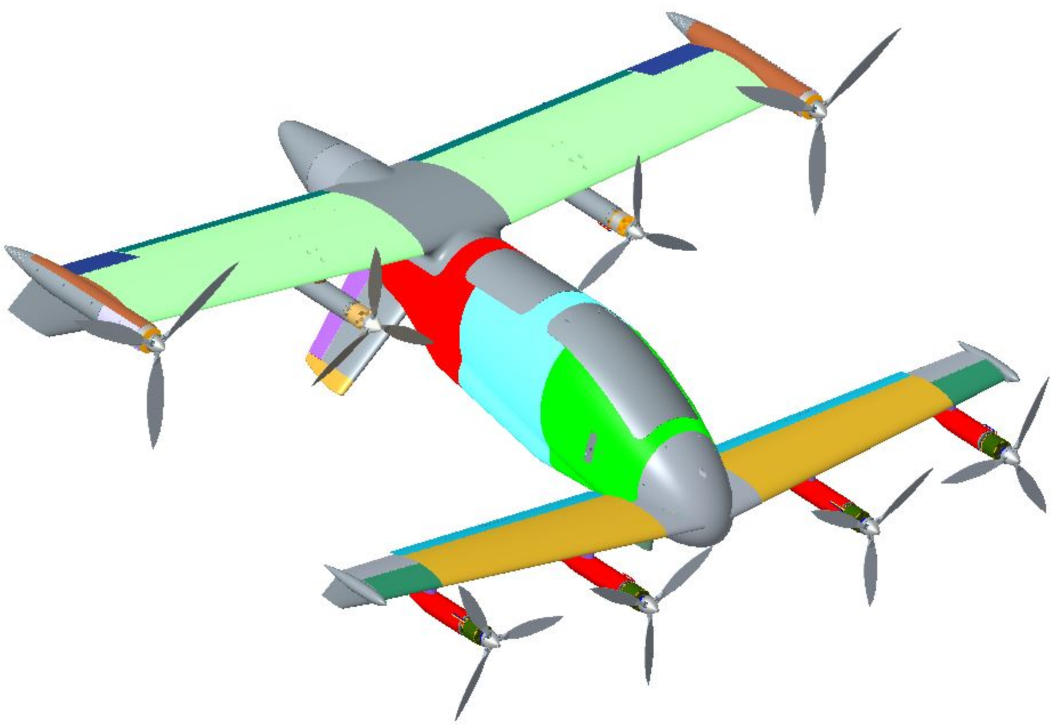

Fig. 2 Isometric view of the full geometry model of the LA-8 in CAD.

The original CAD model of the LA-8 incorporates all of the components needed to actuate and flight test the model including servo actuators, hinges, cooling geometry modifications (e.g NACA ducts), etc. All of these components and geometry features were removed to simplify the LA-8 model. The half model of the finalized LA-8 in FlightStream can be seen in Fig. 3. Symmetry mode with the half model was used for the unblown cases. Due to asymmetries in rotation and thrust from the propellers, a full model was created and used for the blown cases. The half mesh had 62,412 triangular panels and the full mesh had 124,834 triangular panels. However, upon solver initialization, most of the triangular panels were paired to form quadrilateral panels, reducing the number of panels by roughly half.

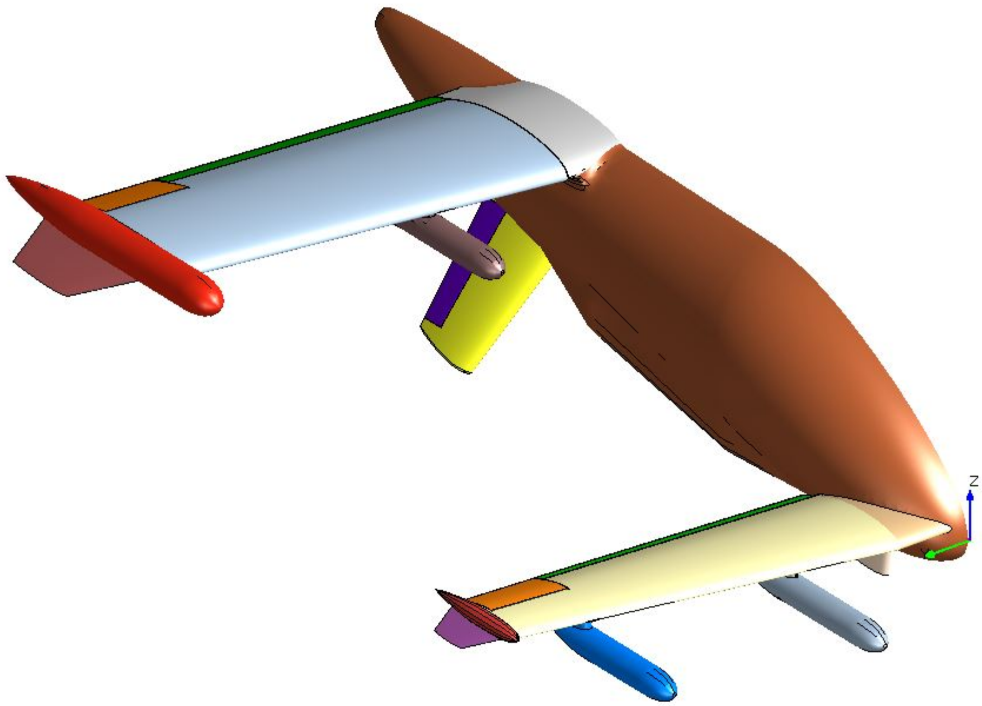

Fig. 3 Isometric view of the half geometry model of the LA-8 in FlightStream.

V. Wind Tunnel Testing

For the comparison to experimental data, the LA-8 has multiple data sets to compare to [6, 7, 12]. The available wind tunnel data varies for each entry. The first entry included one-factor-at-a-time (OFAT) testing for both a propeller-on and propeller-off case. However, the first tunnel test used different propellers than the second and third tests, therefore, the power-on data is not comparable with power-on data from the latter two tests. The second entry completed a full design of experiments (DOE) test of the newly configured LA-8 with the propellers on the vehicle. The third entry into the wind tunnel was split into two segments. The first segment completed an OFAT test for a variety of dynamic pressures with no elevons, ruddervators or propellers. Each dynamic pressure investigated flaps at a half deflection (20 degrees) and zero deflection. The second part of the third wind tunnel entry performed a full DOE experiment without propellers to mirror the previous DOE test that was completed in the LA-8's second entry. Results will be compared to the DOE data sets primarily due to the variability in the data collected, which may be attributed to the disassembly and reassembly each time the vehicle went to the wind tunnel and the configuration change between the first and second entry. The third entry OFAT data, in addition to the DOE propellers-off response surface models, will be used to compare to the propellers off FlightStream analysis runs because of the consistency of the data collected between both tests and because of the limited ranged of angle of attack in the DOE response surface models (6 degrees positive and negative). For the DOE testing, the DOE test matrix had limits that were identified from the first OFAT test in order to enforce restrictions on the balance and model strength as well as examine only the expected flight envelope for the LA-8 [7]. The main considerations during the DOE test matrix development were the angles of attack, propeller RPMs, and wing angles with dynamic pressure being the controlled variable. Although this was a limitation for the powered airframe test case, the same boundaries were applied to the DOE testing of the unpowered airframe. For each test case, the angle of attack range that will be examined in FlightStream will match the data collected during the most extensive test.

Figure 4 shows consistency from the wind tunnel propeller-off no flap data collection over the various testing campaigns. The first set of OFAT data collection sparsely varied dynamic pressure, but the tested dynamic pressures are lower than what was captured in the third tunnel entry OFAT test. In Fig. 4, it can be seen that there is slight variance in wind tunnel results at higher coefficient of lift (C_L) values, including the stall point, between dynamic pressures. The differences between the dynamic pressures could be attributed to wind tunnel operations or potentially Reynolds number effects on the airfoil, considering that the Reynolds number across the wings is low. OFAT data for the propeller-on case was not collected and the results of the DOE test will be directly shown in the Section VI. Full discussion of the DOE modeling results can be found in Ref. [12].

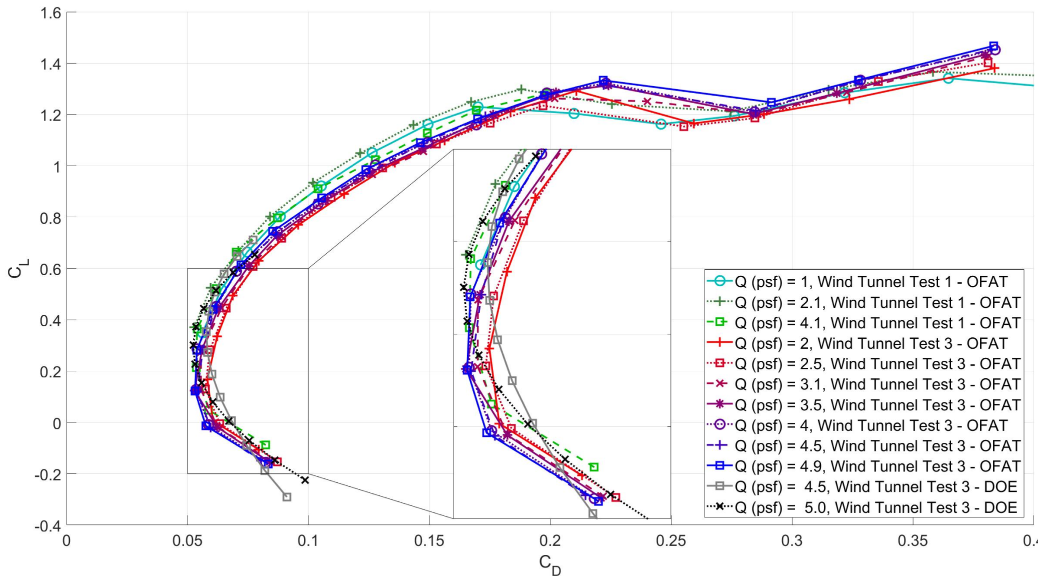

Fig. 4 LA-8 wind tunnel results for variation in dynamic pressure, C_L vs C_D.

VI. Results

The following subsections provide a comparison of the FlightStream results to wind tunnel data for four configurations of interest. The four configurations are the combinations of propellers-on and -off and flaps set to zero and 20 degrees deflection. The remaining control surfaces were set to zero deflection in all cases. All cases were run for 400 iterations, resulting in residuals of pressure and velocity on the order of 10^{-5} at convergence.

FlightStream can produce results using a vorticity formulation or a pressure formulation. The vorticity formulation calculates loads directly from the surface vorticity of the potential flow solution and includes no viscous effects other than a skin friction drag estimate. The pressure formulation converts the surface vorticity to pressure and further augments the solution with flow separation models. The results of both formulations were recorded and are shown here.

A. Propellers-off

Figures 5 and 6 show the propeller-off lift curve comparisons for the zero and 20 degree flap configurations, respectively. In both cases, the pressure solution was more in agreement for the lift prediction than the vorticity solution over the entire angle of attack range compared to the wind tunnel data. The pressure solution still produced a noticeable overprediction in the flapped case, but the magnitude of the overprediction was about half of that of the vorticity solution in the linear region. The discrepancy between the pressure solution and experimental lift coefficients is suspected to be a product of the decoupled boundary layer formulation employed by the current version of FlightStream. According to the developers, a coupled boundary layer solver is currently under development to address this error. At higher angles of attack, both pressure solutions show a flattening of the lift curve due to stall, but the angles of attack at which stall begins is underpredicted. In the post-stall region, the pressure solution lift coefficients were within 15% of the experimental values.

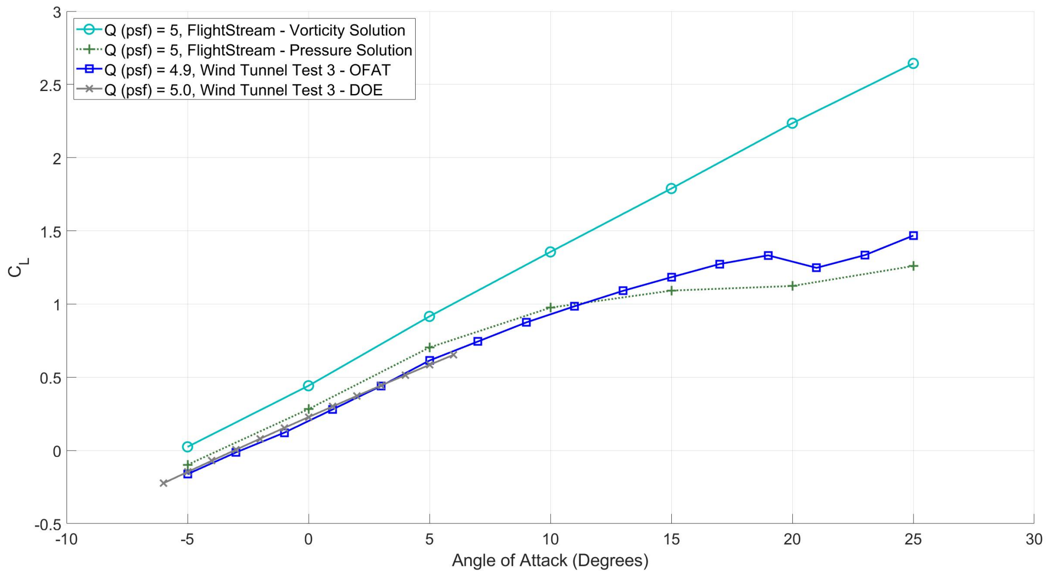

Fig. 5 Comparison of FlightStream results and wind tunnel data for zero flaps and propellers off, C_L vs angle of attack.

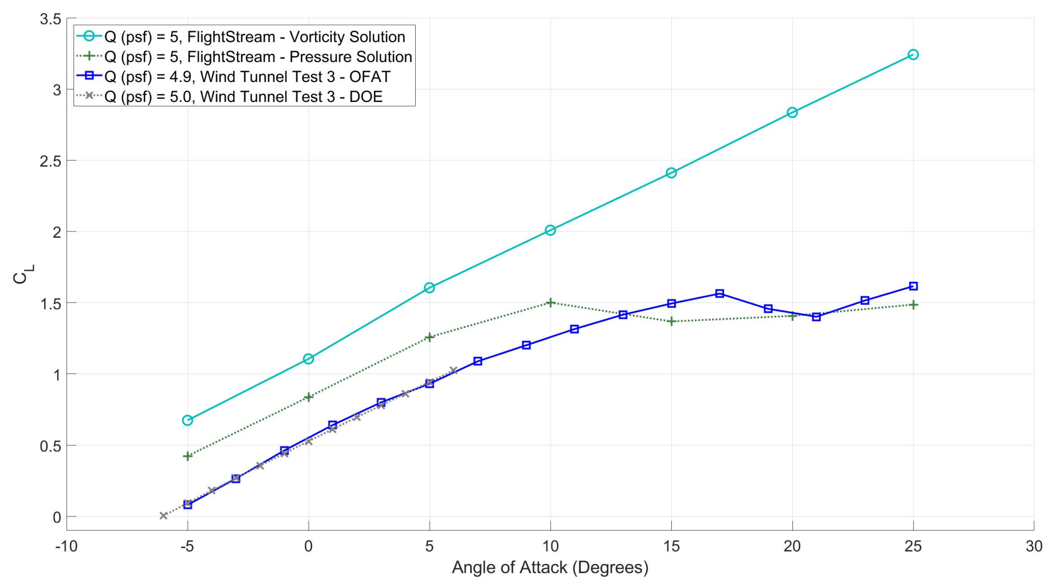

Fig. 6 Comparison of FlightStream results and wind tunnel data for 20 degree flaps and propellers off, C_L vs angle of attack.

Figures 7 and 8 show the propeller-off drag curve comparisons for the zero and 20 degree flap configurations, respectively. In both cases, the vorticity solution underpredicted the drag coefficient over the entire angle of attack range. The pressure solutions were less in agreement with the wind tunnel data, overpredicting in the region near zero angle of attack and increasingly underpredicting at more extreme angles of attack.

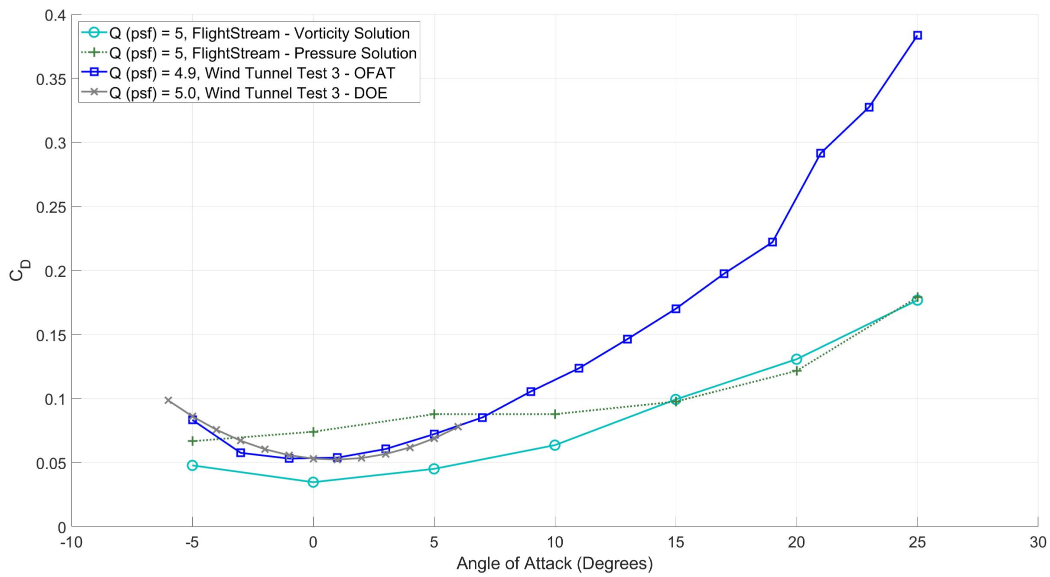

Fig. 7 Comparison of FlightStream results and wind tunnel data for zero flaps and propellers off, C$_D$ vs angle of attack.

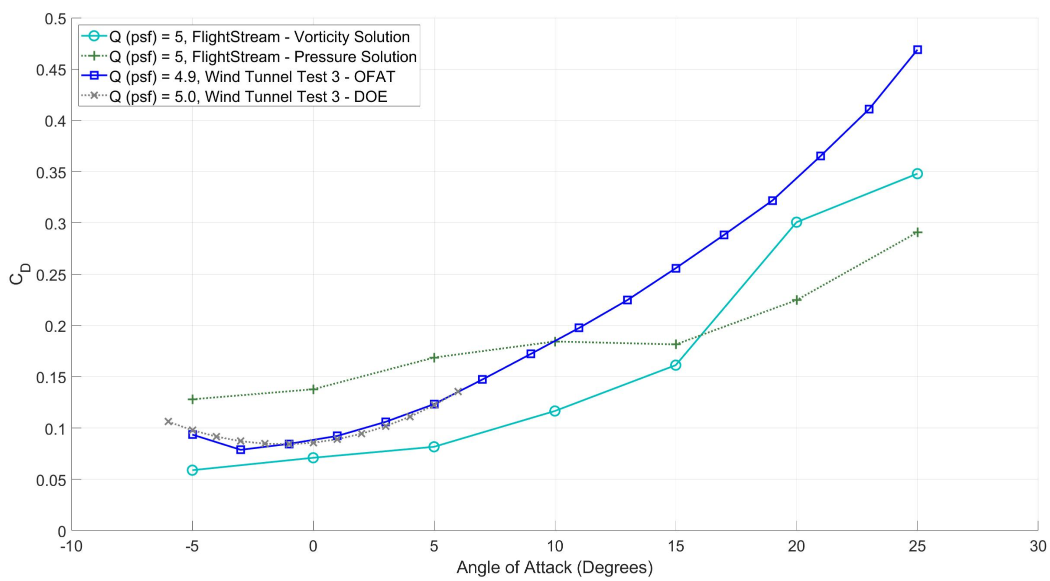

Fig. 8 Comparison of FlightStream results and wind tunnel data for 20 degree flaps and propellers off, C$_D$ vs angle of attack.

B. Propellers-on

The LA-8 wind tunnel test did not include individual propeller thrust measurements so exact thrust coefficients were not available for the FlightStream propeller-on cases. Instead, thrust coefficients and rotation speeds were approximated using data from isolated propeller tests [13]. A consequence of this approximation is the lack of propeller-airframe and propeller-propeller interactions that would have affected the propellers mounted on the LA-8. The blockage of the wings behind the propellers would likely have resulted in a higher thrust coefficient than in the isolated test. However, the rear propellers being partially in the slipstream of the front propellers would cause the LA-8 installed thrust coefficient to be lower than the isolated thrust coefficient, countering the blockage effect.

Figures 9 and 10 show the propeller-on lift curve comparisons for the zero and 20 degree flap configurations, respectively. Compared to the wind tunnel modeling data, the vorticity solution in Fig. 9 is more in agreement in magnitude than the pressure solution for the lower angles of attack, whereas the pressure solution was more in agreement in Fig. 10 across the entire inspected range of angle of attack. However, this may be a result of an incorrect propeller thrust coefficient.

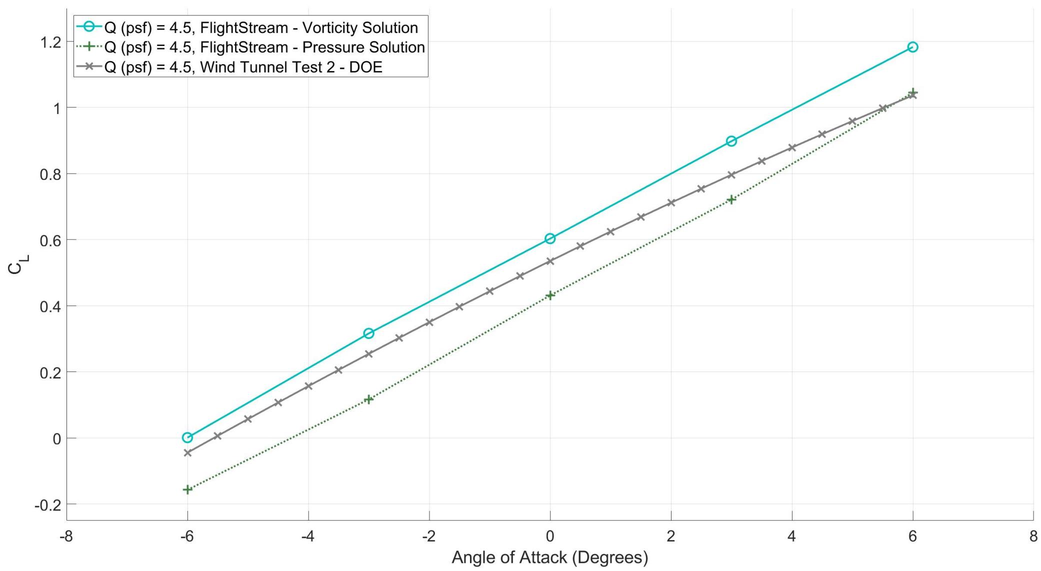

Fig. 9 Comparison of FlightStream results and wind tunnel data for zero flaps and propellers on, C_L vs angle of attack.

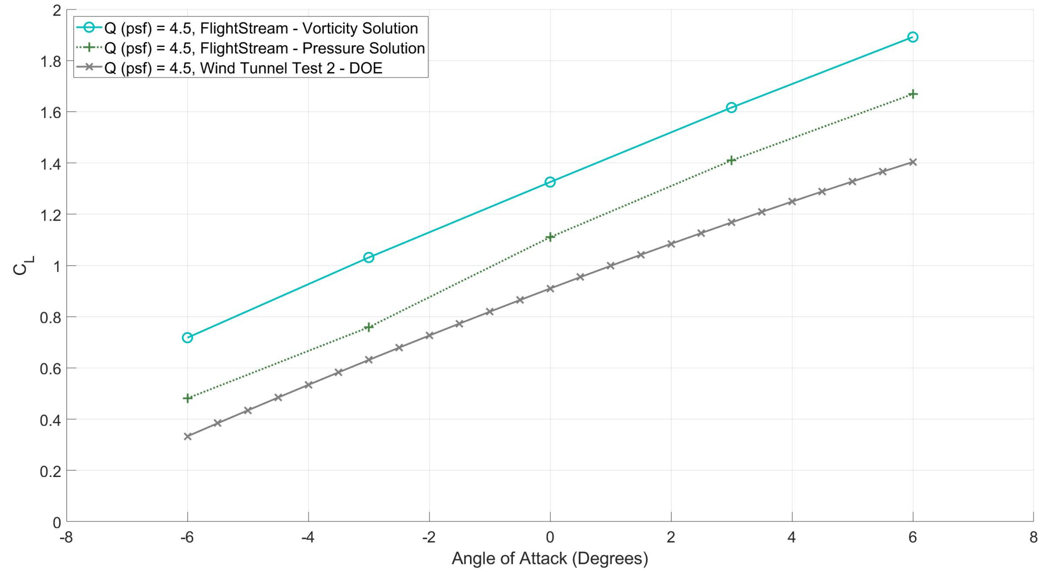

Fig. 10 Comparison of FlightStream results and wind tunnel data for 20 degree flaps and propellers on, C_L vs angle of attack.

Figures 11 and 12 show the propeller-on drag curve comparisons for the zero and 20 degree flap configurations, respectively. The error seen in the propeller-on drag coefficient predictions are larger in magnitude than that observed in the propeller-off results, strongly suggesting that the propeller thrust was indeed overestimated. Thrust offset aside, the vorticity solutions reflect the drag trend more accurately than the pressure solution in both cases, while the pressure solution captures the magnitude of the drag coefficient more closely than the vorticity solution, when compared to the wind tunnel modeling data.

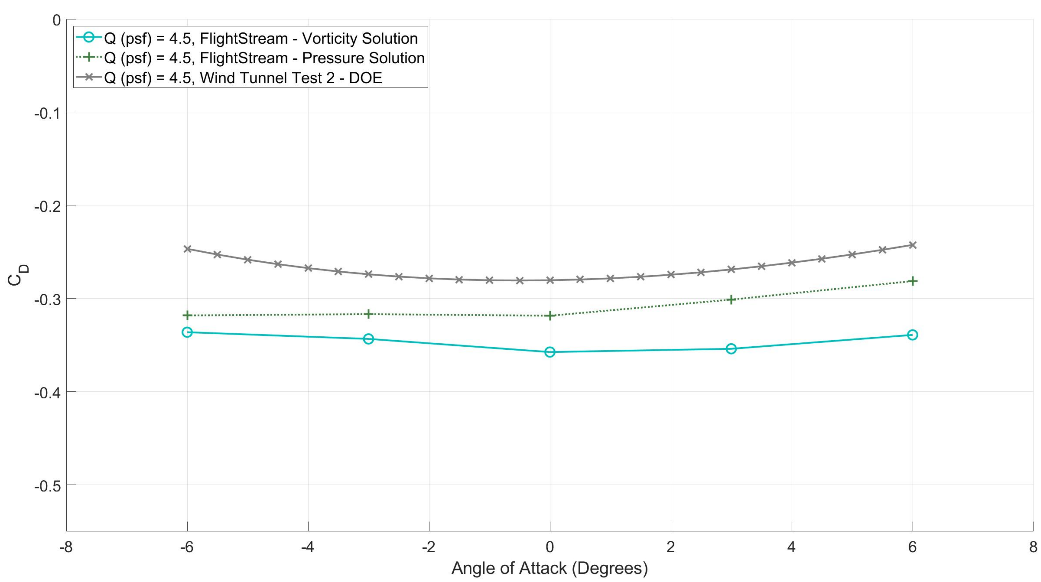

Fig. 11 Comparison of FlightStream results and wind tunnel data for zero flaps and propellers on, C_D vs angle of attack.

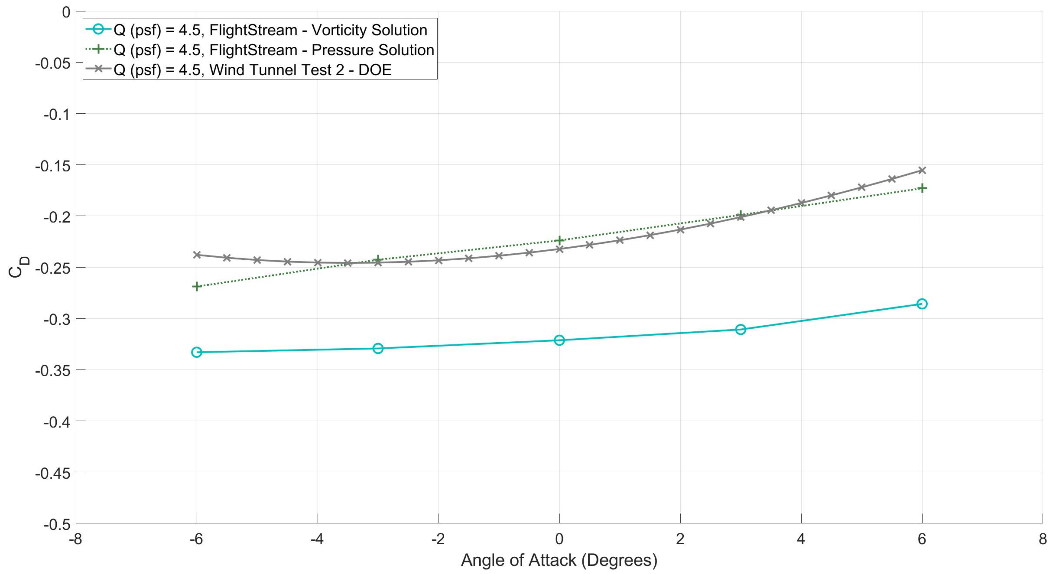

Fig. 12 Comparison of FlightStream results and wind tunnel data for 20 degree flaps and propellers on, C_D vs angle of attack.

VII. Conclusions

After completion of importing, setting up, and analyzing the LA-8 into FlightStream, a few assessments of FlightStream can be drawn. FlightStream showed that it could handle the multi-component, detailed model of the LA-8. Additionally, using this detailed model with high-lift devices and hinged control surfaces, the analysis consistently converged after performing 4 different test cases, each unique in their set up. FlightStream produced trends for the propeller-off test cases, pressure solution for lift and vorticity solution for drag, similar to the wind tunnel test results. The magnitude of the FlightStream results for the propeller-off test cases overpredicted the lift results, which is expected without the coupled boundary layer solver, and underpredicted the drag results. Additionally, with the propellers added into the analysis, FlightStream was able to continue to provide stable results, however, the trends began to deviate, more evidently in the coefficient of drag results than the coefficient of lift results. Finally, the magnitude of the propeller-on FlightStream tests was within an order of magnitude, but were overpredicted by both the vorticity and pressure solutions, which may be a result of incorrect thrust coefficients. Overall, the comparisons of the FlightStream results and the LA-8 wind tunnel data show usefulness in the investigated design space.

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