NUMERICAL ANALYSIS OF WING-TIP MOUNTED PROPELLER INTERACTION USING ACTUATOR DISK MODEL

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ABSTRACT

The development of virtual prototype of aircraft mechanisms is an essential phase to help industrialists and scientists to validate the experimental results and optimize its behavior. For e-aircraft development utilizing a propeller propulsion system on aircraft and its aerodynamic effects of propellers-wing interaction are becoming very important studies for the design of electric or distributed propulsion aircraft. This development requires a good understanding of the propeller effect in general and wing-tip mounted propeller effects on overall performance of the aircraft. Computational investigations of the aerodynamic interaction of wing-tip mounted propeller has been performed using commercial software Simcenter STAR-CCM+. Geometry, test conditions and required post processing data is made available by AIAA as part of their global Workshop for Integrated Propeller Prediction (WIPP). In this study, we have tried to investigate and obtain the quantified insight into the aerodynamic and propulsive efficiency gains of a wing-tip propeller configuration.

In the initial part of this numerical analysis, a CFD simulation has been performed in which the propeller has been represented by an actuator disk model. Modelling propeller driven flows in CFD can often be a very time consuming and computationally expensive process, due to the necessity of highly refined spatial discretization and very small-time step sizes. The Virtual Disk Model in Simcetner STAR-CCM+ significantly decrease the cost of these computations. Along with virtual disk model, the compressible ideal gas flow is solved with a classical Reynolds-Averaged-Naiver-Stokes (RANS) solver as a steady state analysis, using a coupled algebraic multi-grid method with a courant number of 10. Turbulence is modelled with the well know SST (Mentor) K-Omega model with 2nd order convection. Computational results for both, with active actuator disk and inactive actuator disk model have been highlighted to distingue the effect of wing-tip mounted propeller on pressure coefficient, lift and drag coefficients. The CFD simulations revealed detailed flow features surrounding the propeller, engine nacelle and the wing surfaces. Detail sections of the vorticity field reveal the propagation of the vortices until far downstream. This flow structure is in good agreement with representative results from studies carried out with non-commercial CFD codes. In future study we wish to include the comparisons with the test results after the test data available from WIPP workshop to validate the results generated from this study.

Keywords: Actuator Disk; Propeller Interactions; CFD; WIPP; e-aircraft.

INTRODUCTION

Electric and hybrid-electric propulsion system for aircraft will help the aviation industry meet the goals set out in the Flight path 2050 Vision for Aviation, which aims to significantly reduce CO2 emissions and noise levels. While the overall number of participants applying innovative architectures related to electrified propulsion for aircraft is relatively small compared to traditional engine, there is a continuous popularity with many R&D centers worldwide actively working on these concepts? The new paradigm for aircraft development which hybrid electric propulsion enables has highlighted significant issues with aircraft certification practices as they exist today. The new propulsion systems may require development of certification standards. Also, the evaluation of the performance of aeronautical elements, especially during the validation and exploitation, aims is to achieve the objectives of quality and safety expectations.
Several key technologies for electrical power and drive systems have matured to the extent where the power and energy density has become suitable for certain aerospace applications. The electrical propulsion systems (e-aircraft) are one of the system which is being explored extensively. In any wing of an aircraft with a finite span, energy is lost due to the lift-induced vortex that forms around and behind the wingtip. The general idea of a wingtip mounted propeller is to recover some of this energy by exploiting the tangential flow around the wingtip. This is done by placing a propeller at the wingtip. Nevertheless, propellers placed at the very end of the wings are nowhere to be found in today's aircraft. This is mostly because of the aero elastic problems, and one-engine out requirements by certifying authorities. These issues can be resolved by scaling down the propeller and using distributed electric propulsion system. Still lots of work going on to evaluate this and quantify the gains.

In late 80s, Patterson and Bartlett [1 and 2], demonstrated the benefits of placing a propeller at the wing-tip in a pusher configuration. They concluded that a 25% reduction in overall power required could be achieved, because of increased propeller thrust and reduction in left-induced drag. In the later years more analytical and numerical work was done [3, 4]. In the articles [5, 6], the researcher had done direct comparisons with conventional propeller-wing layout and the wing-tip -

mounted configuration, the later configuration showed a drag reduction of around 15%. This aerodynamic benefit increased upon increasing the wing lift coefficient and propeller thrust gain as well.

Recently there has been renewed interest in the concept of wingtip-mounted propellers. NASA has reinstated its legendary X-Plane series. The newest X-Plane, the X-57 Maxwell, it aimed at demonstrating distributed electric propulsion using multiple propellers placed along the span of the wings as shown in the Fig. 1. Several large -scale projects in the field of personal air transport are ongoing with the tag of e-aircraft. This hybrid electrical propulsion system is also being explored for skydiving mission and other applications [7]. One of the NASA report [8] also heighted the projected timeline for technical readiness for hybrid electrical propulsion systems as shown in Fig 2.

FIGURE 1: NASA'S X-57 MAXWELL

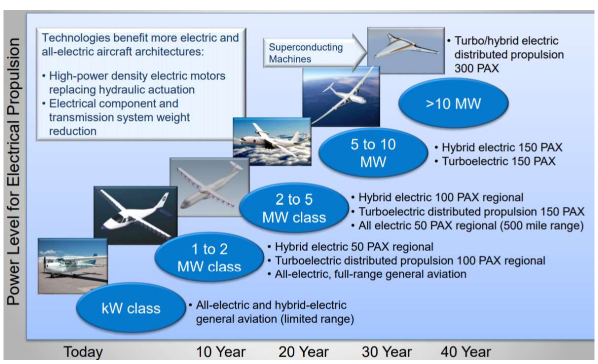


FIGURE 2: PROJECTED TIMELINE FOR TECH READINESS

The end objective of this study is to obtain quantified insight into the aerodynamic and propulsive efficiency gains of a wing-tip mounted propeller configuration. In the initial part of this numerical investigation, a CFD simulation using Simcenter STAR-CCM+ commercial software [9] has been performed in which the propeller has been represented as a virtual disk model. Horlock [10] presented an overview of the principles of various actuator disk models and their applications to various problems. Rosen and Gur [11] presented a detailed literature survey of the development of these models over the years. Moens and Gardarein [12] assessed the capability of the actuator disk model to predict the propeller slipstream interaction for an aircraft for both cruise and take-off configurations and evaluated the disk model as an efficient and relatively accurate computational fluid dynamics (CFD) tool. Computational results for both, with active virtual disk and inactive virtual disk model have been highlighted to distingue the effect of wing-tip mounted propeller on pressure coefficient, lift and drag coefficients. In future study it is recommended to include the comparison with test results to validate the data generated from this study.

ACTUATOR DISK MODEL.

Modelling propeller driven flows in CFD can often be a very time consuming and computationally expensive process, due to the necessity of highly refined spatial discretization and very small-time step sizes. A numerical analysis of propellers can be achieved at different levels of complexity. The Virtual Disk physics model in Simcetner STAR-CCM+ significantly decrease the cost of these computations. The action of the actuator disk model on the flow field, also referred to as the momentum theory, is perhaps the most basic representation of a propeller. It is already a well-determined concept; several paper and articles have been published to present different applications. Various distributions of different fidelity are possible to model the action of the actuator disk, which negated the need to resolve the blade geometry, drastically decreasing the required mesh size. The actuator disk treatment is practical when information about the rotor/propeller behaviors is available and its effect on the surrounding is desired. Modelling propeller driven flows in CFD can often be a very time consuming and computationally expensive process, due to the necessity of highly refined spatial discretization and very small-time step sizes. The Virtual Disk Model in Simcetner STAR-CCM+ works to significantly decrease the cost of these computations.

For the Virtual Disk Model, there are four methods available in STAR-CCM+: Body Force Propeller Method, Blade Element Method, 1D Momentum Method and User Defined Method. In the current study, Body Force Propeller Method of the Virtual Disk model have been used to represent wing-tip mounted propeller and its effect on the wing surface. This method is useful if you do not require the detailed flow field around the propeller, but more importantly need the correct propulsion specification. The Body Force Propeller method allows you to model the propeller, without the added cost of modeling the propeller geometry with a fine mesh and smaller time scales. Several variables needed to be define the operating condition that applies to the body force propeller method.

The body force propeller method uses the following approach;

- Definition of a virtual disk regarding position and direction in which thrust is produced
- Specification of a propeller performance curve
- Specification of an operating point (for example, rotational speed)
- Specification of an inflow method

As a result, the distribution of the axial and tangential forces of the modeled propeller and its effect on the flow is calculated. The integration of these forces over the disk gives the thrust and torque of the propeller.

CFD SETUP

The complete simulation process, from meshing through to post-processing have been performed entirely within the Simcenter STAR-CCM+ integrated environment.

GEOMETRY MODELLING AND MESH:

A CAD model of geometry available with the dimensions as shown in Fig 3 adopted from WIPP AIAA Aviation's workshop, has been imported and prepared for CFD analysis. Boundaries and surfaces like inlet, outlet, wing surfaces have been segregated to setup the boundary conditions and post processing for forces accounting for lift/drag and pressure coefficients. Imported geometry are remeshed to improve the overall quality of an existing surface and optimize it for the volume mesh models. Fig 4. Shows the discretized model with a total of 4M trimmed hexahedral cells for entire volume. We have also added the wake refinements to capture the flow conditions behind a body as shown in Fig 5A.

The setup of the virtual disk model of the body force propeller method does not require the creation of a separate region to which the model is then applied. We can create the shape of the virtual disk by specifying the relevant parameters such as radius, thickness, and orientation to an existing mesh. We can visualize the virtual disk (Fig 5B) with the help of in build field functions that become available when the virtual disk model is activated.

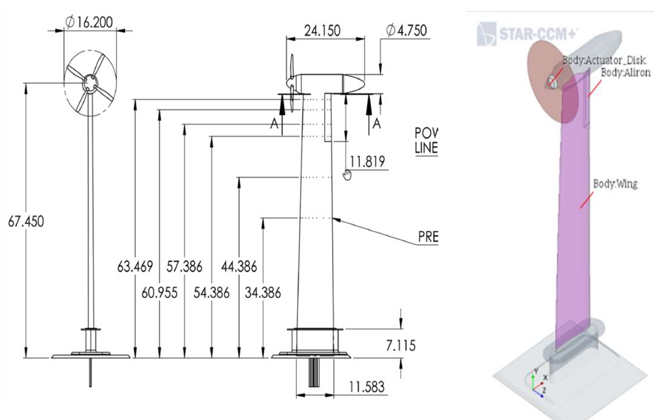


FIGURE 3: GEOMETRICAL DESCRIPTIONS AND SURFACES FOR THRUST, LIFT/DRAG.

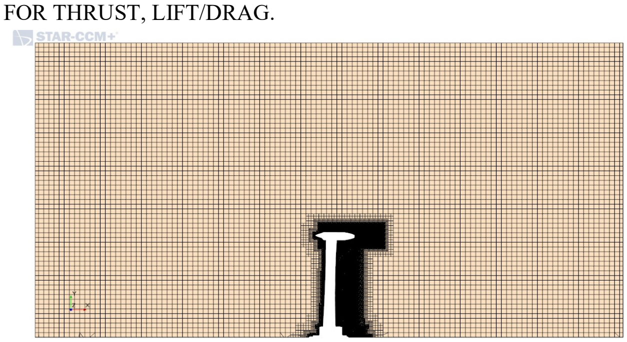


FIGURE 4: DISCRETIZED MODEL

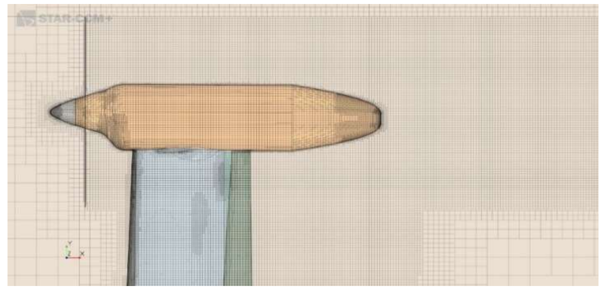


FIGURE 5A: WAKE REFINED MESH

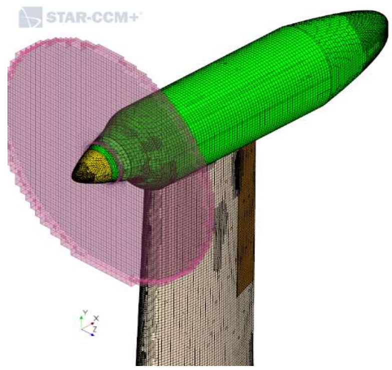


FIGURE 5b: VIRTUAL DISK WITH THE MESH LINES

FLOW SOLVER

A density-based couple solver have been used for the simulation. The coupled system of equations is discretized in time by either the implicit or the explicit time-integration scheme in conjunction with a Newton-type linearization of the fluxes. Two upwind based schemes AUSM+ flux-vector splitting scheme and Roe's flux-difference splitting scheme are available for evaluating the in viscid fluxes. The equations for turbulence quantities are solved in a segregated manner outside the coupled solver. The Coupled Flow Model can be used in both the steady solution and transient solution. For steady-state simulations, the coupled system of equations is discretized in time and time-stepping is performed until a quasi-steady-state solution is obtained. The density-based methods have recently been extended to low-Mach number and low-Reynolds number with developing appropriate preconditioning. The preconditioned "Unsteady Low-Mach Preconditioning" is available in STAR-CCM+ to improve convergence and accuracy of the coupled solver for incompressible flows at low speeds. For further reading on the preconditioning and dual-time stepping please refer to the STAR-CCM+ user guide or Ref [9].

BOUNDARY CONDITIONS AND PHYSICS MODELS

A summary of the boundary conditions is given below, and the depicts of the 3D domain is shown in Fig 6,

- Air: Ideal Gas
- Turbulence Model: SST k-omega, all y+
- Propeller speed: 8000 RPM
- Mach: 0.08
- MAC: 10.15in
- Static Pressure:15 psi
- Outlet: Pressure outlet

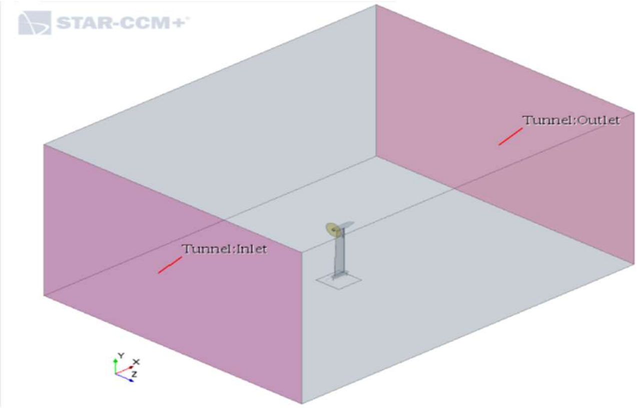


FIGURE 6: DEPICTS THE 3D DOMAIN

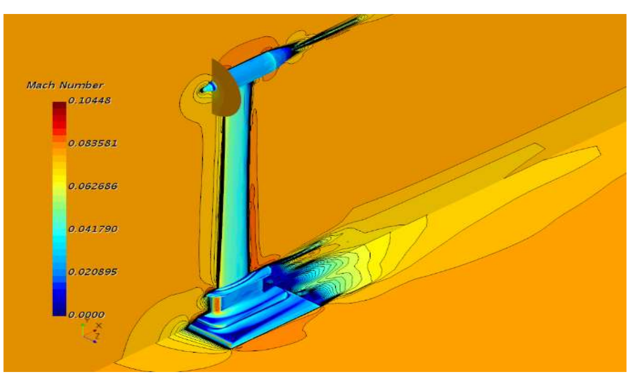
To set up and run the body force propeller method requires to define the following items:

- dimensions and location of the disk,
- Orientation of the disk axis.
- This orientation defines the direction of the thrust force, propeller performance data, where the thrust coefficient K_T and the torque coefficient K_Q are provided as a function of advance ratio J and velocity plane on which to obtain an average velocity and density for the inflow surface of the virtual disk.

The propeller performance is available from experiment in terms of thrust coefficient, torque coefficient, and propeller efficiency as a function of advance ratio which is supplied in tabular format in STAR-CCM+ as an input conditions to virtual disk model.

RESULTS

One of the principle advantage of CFD simulation regards the ability to visualize the flow, which gives the engineer a valuable insight into the performance of the design, not easily available using alternative means. For instance, we can obtain a good visualization of the flow field and pressure distribution around the wing. Currently all results presented here are without the virtual disk model. We intended to submit the comparative results along with virtual disk model in our full-length paper once the extended abstract paper accepted. Fig 7 shows a flow field, pressure field and close-up of the velocity field near propeller mounted wing-tip.



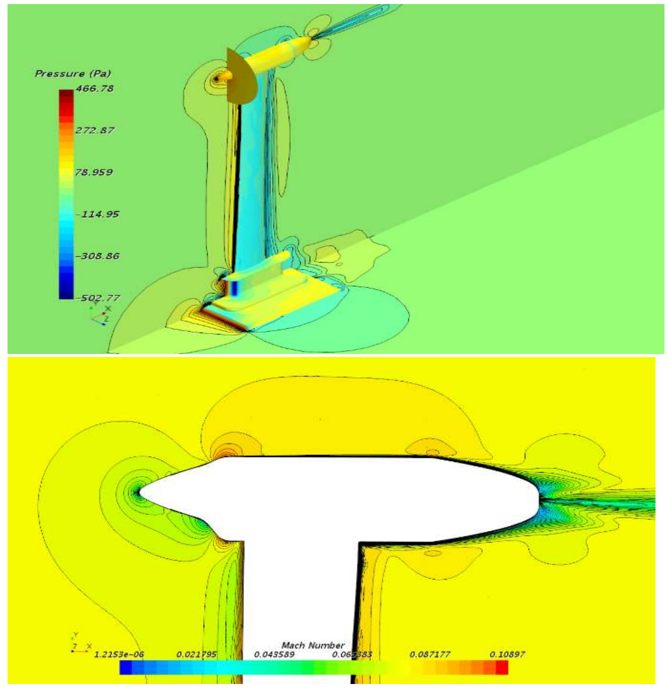


FIGURE 7: FLOW FIELD AND PRESSURE DISTRIBUTION AROUND THE WING WITHOUT THE VIRTUAL DISK MODEL

For monitoring and plotting the forces, we need to create several reports for the different forces such as drag, Lift, and the pressure coefficient plots at different sections of the body. Some of these plots also help us judge the convergence of the solutions. The net forces in X direction which provide the drag coefficient information's is shown in Fig 8a. And net forces in Z direction which provide us the lift coefficient is shown in Fig 8b. From the results we can clearly see that solutions are well converged as there is no fluctuation on forces as simulation progresses after 200 iterations.

Wing pressure at 6 span stations (height above the tunnel floor) depicted. The pressure coefficient on four section mid span at Y = 34.386 in along with Y = 44.386in, Y = 60.95in and Y = 63.47in as shown in Fig 9. We can clearly see from the plot that, pressure coefficient has some distortion because of the placement of the propeller engine installations. It would be interesting to compare these results while actuator disk model is active.

To visualize the vector field, we have plotted the Line integral convolution scene on a plan section near mid span of the wing as shown in Fig 10. This technique has the advantage of being able to visualize large and detailed vector field in a reasonable display area.

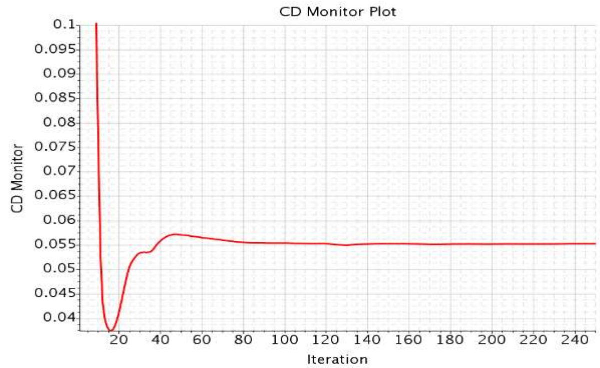


FIGURE 8A: DRAG COEFFICIENT PLOT ON WING SURFACE

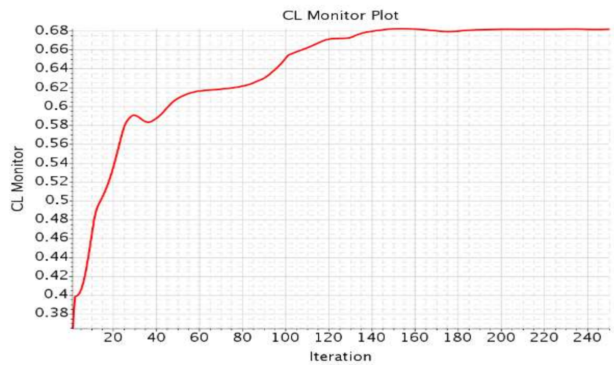


FIGURE 8B: LIFT COEFFICIENT PLOT ON WING SURFACE.

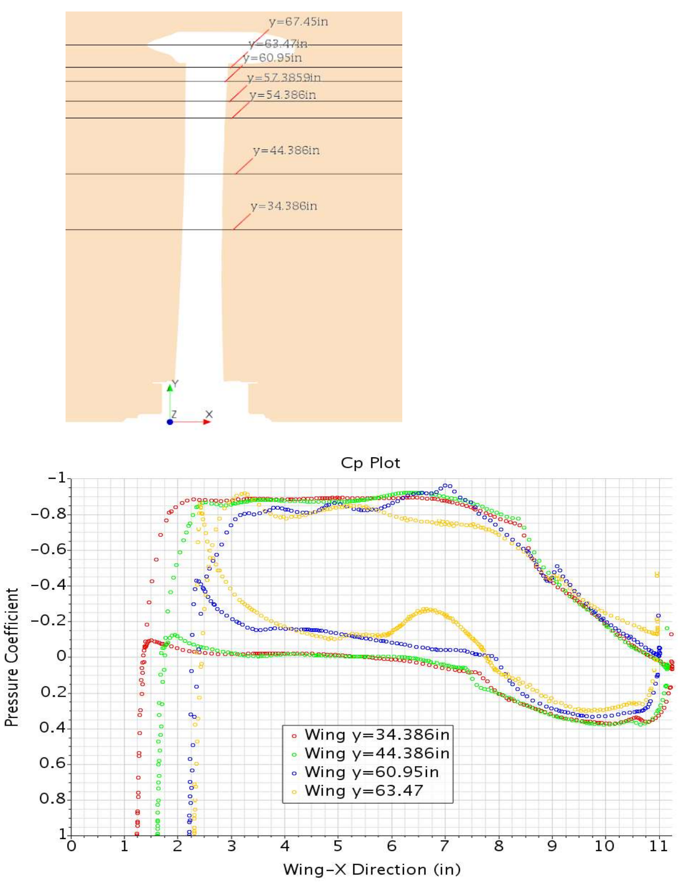


FIGURE 9: SECTIONS AND PRESSURE COEFFICIENT PLOTS ON

CONCLUSION

Numerical simulation of a wing-tip mounted propeller has been performed using actuator disk model. The results discussed demonstrate that the flow field around the wing-tip propeller, without the actuator disk. With the actuator disk model active, slipstream does affects the aerodynamic performance of the wing which will be discussed in full length paper. Overall it can be concluded that the wing-tip mounted configuration does increases the lift capability and CFD analysis help us obtain lots of data which is useful to study the effect of propeller interaction with the wing surface and with the Aileron (control surface).

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