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Benefits of Boundary Layer Ingestion with Froude's Propeller Theory

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Boundary layer ingestion is an aeropropulsive concept that addresses the future goals of reduced emissions and fuel consumption by aircrafts to mitigate the adverse impact of aviation industry on the environment. This requires synergestic airframe and propulsion system that accounts for increased aircraft efficiency. In this paper, an integrated airfoil and BLI propulsor configuration is compared with a baseline freestream configuration to analyze the benefits of the boundary layer ingestion. The results are quantified in terms of power consumption, propulsive efficiency and aerodynamic parameters.

I. Nomenclature

ρ = freestream density
T = Thrust
ΔP = Pressure Difference
A = Area of disc cross section
$\dot{m}$ = mass flow rate

II. Introduction

With increasing concern towards the global environmental conditions, it becomes requisite for aviation industry to reconsider its existing impact on the climate change. With a global contribution of about 4.9 percent by the aviation sector in anthropogenic global warming, The Paris Agreement targets to control the emissions and global warming by limitting the increase in temperature to $1.5°C$ (well below $2.0°C$ above preindustrial levels). The initiative of environmentally sustainable air travel in year 2050 led by The Advisory Council for Aviation Research and Innovation in Europe (ACARE) points to a 75% reduction in CO_2 emissions per passenger kilometre and a 90% reduction in nitrogen oxide NO_x emissions. It also attributes to a 65% noise reduction of flying aircraft. Therefore, to address the increasing air transport and need for more environmental sustainability Boundary layer ingestion works effectively by increasing the fuel efficiency.

Boundary layer ingestion is a concept of placing aircraft engines or propulsors at the rear of fuselage, so that the slower air is ingested into the engines, which is further accelerated by the engines out the back reducing total drag. This requires integration of airframe and propulsion system unlike current aircraft configurations where the interaction is minimum. Propulsors with boundary layer ingestion generate propulsive force with less power input than conventional engines. A part of airframes's boundary layer or wake is ingested by this noval propulsion system that increases overall aircraft efficiency and reduces emissions.

NASA's STARC-ABL is a conceptual aircraft with tube wing configuration consisting of two turboelectric jet engines and a rear fuselage BLI fan. When compared with conventional technologies, STARC-ABL has 7% block fuel burn reduction for the economic mission, and 12 block fuel burn reduction for the design mission. D8 Double Bubble is a modified tube wing configuration aircraft with a wide lifting fuselage. Relative to similar baseline models, D8 has potential to achieve 71% reduction in fuel burn and 87% reduction in LTO NO_x . When compared with its BLI and non-BLI configuration, the former showed 6% reduction in electric power consumption at cruise condition.

In this study, a symmetric airfoil is considered as a fuselage with Froude's Actuator Disk as a propulsor placed behind the airfoil in freestream and BLI configuration respectively. After carrying out analysis in ANSYS CFD, the aerodynamic and propulsive parameters are demonstrated. The benefits of the BLI configuration are validated in terms of the power saving coefficient as well.

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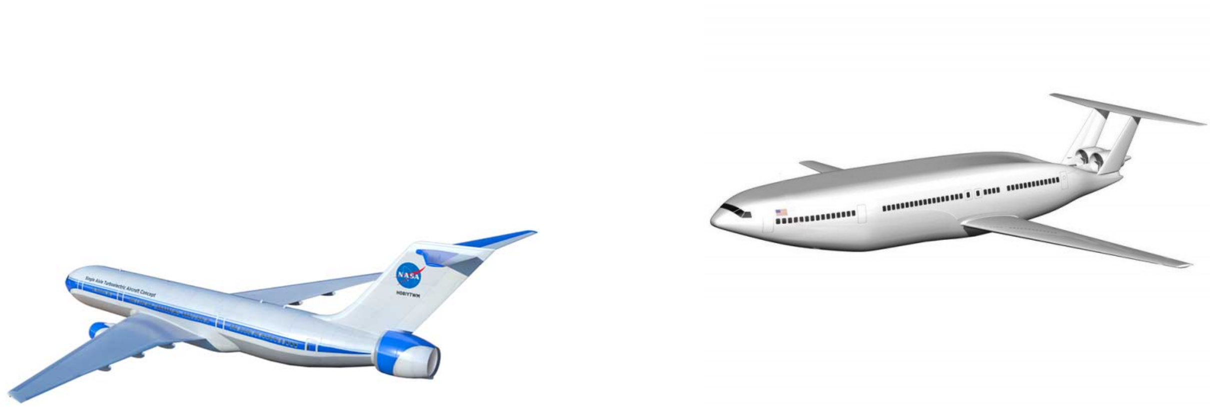

Fig. 1 Conceptual Aircraft Design with BLI Concept; NASA's STARC-ABL (left); D8 Double Bubble (right)

III. Boundary Layer Ingestion

Boundary layer ingestion requires synergestic airframe and propulsion system that contributes to increase in propulsion system performance. Therefore, due to this mutual impact, part of drag is induced by the propulsion system and part of thrust is induced by fuselage. In conventional configuration, airframe boundary layer and propulsor jet represent wasted kinetic energy. In order to produce combined wake and jet with lower kinetic energy and reduced losses, re-energizing of slow moving air through BLI is conducted that also increases overall aircraft efficiency.

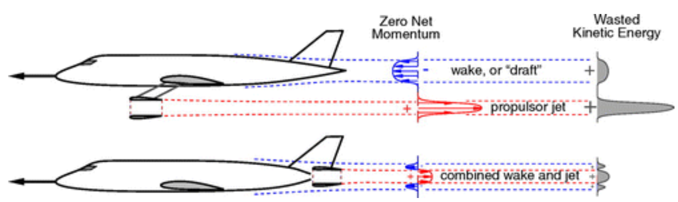

Fig. 2 BLI Concept

Figure represents two configuration: Fig no boundary layer ingestion (conventional configuration with podded engine) and Fig ideal boundary layer ingestion (100% of wake ingetion by the engine/propulsor). In the case of podded engine configuration, incoming flow of the engine is at freestream velocity V_∞ . The engine accelerates the flow to velocity V_e (greater than V_∞) to balance the momentum deficiet due to the airframe drag. For the ideal BLI configuration, the engine/propulsor ingests slow moving boundary layer flow V_w and then accelerates the flow upto freestream velocity V_∞ .

BLI configuration accounts for lower power consumption that is due to reduction in jet, surface and wake diisipiation. With reduced power requirement to obtain same thrust, propulsor jet dissipiation is reduced that increases propulsive efficiency. Smaller partially embedded nacelles that exhibit lower surface velocities are responsible for lesser surface dissipiation. Propulsors ingesting boundary layer, partially eliminate fuselage viscous wake, decreasing the wake dissipiation. Body wake is regarded as power input for the propulsion system. Due to this wake ingestion, aircraft forward speed is maintained with lower outflow velocity magnitude. This attributes to reduced velocity at propulsion system inlet. The reduced dissipiation in BLI contributes to its aerodynamic benefit. Lighter weight due to smaller engines and nacelles relates the re-optimized design or airframe to its system level benefit.

Propulsor and airframe interaction also effects the boundary layer and the pressure distribution. As the flow accelerates, profile drag increases because of low pressure at the rear end that increases pressure difference. Moreover, intake duct distortion contributes to the approach losses. These losses are accompanied by viscous, shock and induced losses. Kinetic energy downstream of the propulsor not in axial direction, adds up to these losses.

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IV. Froude's Propeller Theory

Froude's Theory clearly describes the impact of the pressure gradients up and downstream of the actuator, leading to contraction of the wake. The work done by thrust is V_{disc}. (disk velocity). In this, the assumptions considered are: pressure drop across the disk is uniform over the area, axial velocity is uniform over the actuator area, there is no rotational velocity in the wake, and static pressure far upstream and downstream is equal to the undisturbed ambient static pressure.

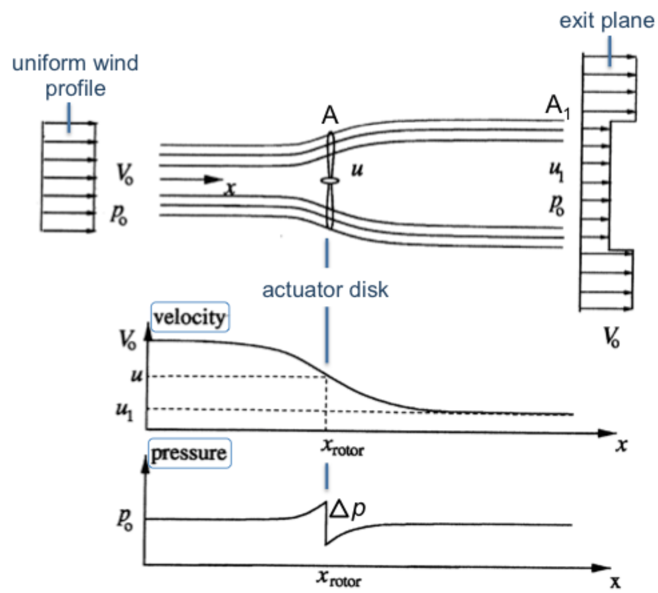

Fig. 3 Actuator Disk Concept

According to this theory, propeller is considered as a thin disc. Let pressure and velocity conditions in far upstream at 1 be P_1 and V_1 respectively. Similarly for disc front at 2 conditions are P_2 and V_2. The disc imparts momentum and energy to the incoming flow and pressure and velocity behind the disc at 3 are P_3 and V_3 respectively. For far downstream at 4 the conditions are P_4 and V_4.

As the disc is thin, we can assume that $V_2 = V_3$. Moreover, the pressure at P_1 and P_4 are equal to the freestream value. On applying and evaluating the Bernoulli's equation for this case, we get,

$$P_2 - P_1 = \frac{1}{2}\rho({V_e}^2 - {V_o}^2)$$

$$T = \Delta P * A$$

On calculating we obtain,

$$P = 2.8265 Pa$$

$$V_{disc} = 9.879 m/s$$

These parameters are applied in the analysis further.

A. Froude Propeller Theory for Freestream Configuration

Froude's actuator disk is used for defining the propeller of zero thickness that creates pressure difference converted at the far field to velocity difference producing thrust. The flow is assumed to be axissymmetric, invicid, and not mixing at the jet edges. Incoming flow velocity is taken as V_∞ and the exhaust velocity (downstream of propeller) is taken as V_e Thrust is calculated as,

$$T = \int\int \rho * V_e * (V_e - V_\infty) dA$$

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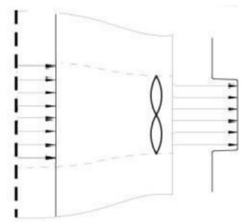

Fig. 4 Inlet Conditions (Freestream)

for constant density and cross section,

$$T = \dot{m} * (V_e - V_\infty)$$

Propulsive power required is the difference between the kinetic energies of the stream tube passes by the propeller downstream and upstream the propeller,

$$P_p = \int\int \frac{1}{2} * \rho * V_e * ({V_e}^2 - V_\infty^2) dA$$

for constant density and cross section,

$$P_p = \frac{\dot{m}}{2} * ({V_e}^2 - {V_\infty}^2)$$

Based on the Power Balance Method, the propulsive power is composed of the useful thrust power and wake power due to velocity perturbations downstream. These components are calculated as,

$$T * V_\infty = \int\int \rho * V_e * V_\infty * (V_e - V_\infty) dA$$

$$E_{wake,prop} = \int\int \frac{1}{2} * \rho * V_e * (V_e - V_\infty)^2 dA$$

Propulsive efficiency is defined as the ratio of useful power to total power. Considering the power decomposition, we can write the respective Froude Formula as,

$$\eta = \frac{T * V_\infty}{T * V_\infty + E_{wake,prop}}$$

Momentum losses between upstream and downstream flows of a stream-tube passes around a body according to the momentum equation and account for the drag. Therefore, drag can be calculated from velocity distribution of wake as,

$$D = \int\int \rho * V_w * (V_w - V_\infty) dA$$

When represented in form of power,

$$D * V_\infty = \int\int \rho * V_w * V_\infty * (V_w - V_\infty) dA$$

Dissipation in the viscous boundary layer and velocity perturbation in the wake constitute the power requirement here. The dissipated energy in the boundary layer is quantified as the energy losses between upstream and downstream in the stream tube that passes around airfoil,

$$\phi_{BL} = \int\int \frac{1}{2} * \rho * V_w * ({V_\infty}^2 - {V_w}^2) dA$$

Energy of the wake can be quantified by the perturbations in the stream tube as,

$$E'_{wake,prop} = \int\int \frac{1}{2} * \rho * V_w * (V_\infty - V_w)^2 dA$$

DOI: 10.13009/EUCASS2023-405

Hence, the total consumption in kinetic energy is equal to drag power that is,

$$D * V_\infty = E'_{wake,prop} + \phi_{BL}$$

B. Froude Propeller Theory for Ideal BLI Configuration

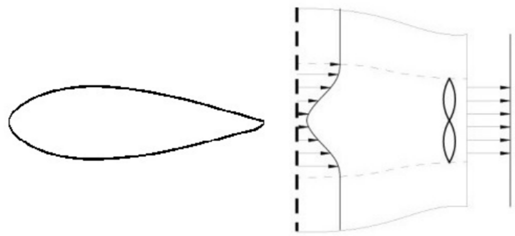

Fig. 5 Ideal Boundary Layer Ingestion

BLI propulsor balances the momentum gap generated by the airframe, therefore minimizing the wake generated. In ideal BLI case, all of the wake is ingested and the jet velocity exactly matches the undisturbed freestream velocity. Here the velocity at the wake is given by V_w. Thus, energy dissipation is only due to the boundary layer viscosity as given by equation in the previous section.

As the stream tube is accelerated to the upstream conditions and all the wake is ingested, kinetic energy added by the propulsor to the stream tube is equal to the losses in the boundary layer. It is calculated as the difference in kinetic energy of the flow in front and behind the airframe as,

$$E_{prop,BLI} = \int\int \frac{1}{2} * \rho * V_w * ({V_\infty}^2 - {V_w}^2) dA$$

So, the power required decreases while the thrust and drag value remains the same. Therefore, BLI reduces power consumption requirement to achieve aerodynamic benefit that can be quoted as Power Saving Coefficient (PSC),

$$PSC = \frac{P_{noBLI} - P_{BLI}}{P_{BLI}}$$

As the thrust is equal to drag, the efficiency can be written as,

$$\eta = \frac{D * V_\infty}{E_{prop,BLI}} = \frac{\phi_{BL} + E'_{wake,prop}}{\phi_{BL}} > 1$$

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V. CFD Methodology

Computational Fluid Dynamics (CFD) analysis is conducted using Ansys CFX and RANS equations with a Shear Stress Transport (SST) turbulance model.

A. Geometry and Meshing

NACA0018 airfoil with a chord length of 1m is used to model the axis-symmetric fuselage body. Propeller is modelled using an actuator disc of radius 0.05m that is 10% of the chord length, placed at 0.04m behind the trailing edge of the fuselage that corresponds to 4% of the chord length.

A rectangular domain (8m x 4m) with a thickness of 0.01m is considered. The fuselage is placed at 0.4m from the domain inlet. The airfoil has number of divisions equal to 200 and the propeller has 100 number of divisions. The body of influence has an element size of 0.05 and the growth rate is 1.2. The generated unstructured mesh has total number of nodes and elements 72052 and 52785 respectively.

B. Boundary Conditions

The boundary condition of the fuselage is no-slip wall. For the freestream case, propeller has a freestream velocity inlet condition and a zero pressure outlet condition. In case of ideal BLI configuration, the propeller has pressure difference boundary condition. It consists of disk velocity as inlet condition and pressure difference as outlet boundary condition (to provide negative pressure gradient for the flow). The boundary conditions are listed as:

Surface	Boundary Condition
Domain Inlet	Velocity inlet
Domain Outlet	Opening (Relative Pressure)
Side Wall	Symmetry
Disk thickness	No Slip Wall
Airfoil	No Slip Wall
Disk Surface	Pressure Difference

Pressure and temperature are set as 1 atm and 25°C respectively. Freestream velocity is 10m/s. Angle of attack is kept zero for this axissymmetric fuselage case.

C. Calculations

For the analysis, the thrust is set equal to the profile drag (of clean configuration) and CFD calculations are carried out. In freestream case, power required by the propeller is calculated as 0.3507 W. Mass flow rate of inlet flow is evaluated as 0.0862 kg/s and the drag coefficient equals to 0.0121164. The propulsive efficiency for this baseline configuration is found to be 97.41%. On the other hand, for the ideal BLI case, power requirement equals to 0.2314 W. Mass flow rate of inlet flow is evaluated as 0.08221 kg/s and drag coefficient is calculated as 0.0114383. The propulsive efficiency is found to be 100.51%. Calculating the drag terms, the boundary layer dissipation is deduced as 1.14714 and wake energy is equal to 0.01148 W.

VI. Results and Discussion

On comparing the two configurations, the primary observation made is reduction in the power consumption. The ideal BLI configuration saves 34.01% of power to that of the baseline configuration. Moreover, the wake is re energized downstream of the disk due to ingestion of slower air upstream of the disk.

Reduction in drag coefficient is also noted amounting to 5.59% less drag for BLI case. The propulsor ingests the slower air and reenergizes the wake downstream the airfoil, thus, providing power consumption and drag reduction benefits.Therefore, this results in increased propulsive efficiency for the BLI case. Propulsive efficiency increments from 97.41% (freestream) to 100.51%(BLI) accounting for a more efficient propulsion system.

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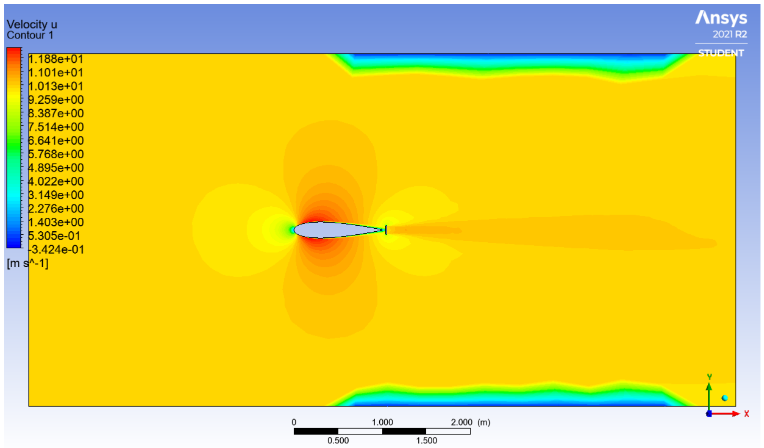

Fig. 6 Velocity Contour for Freestream condition (Baseline)

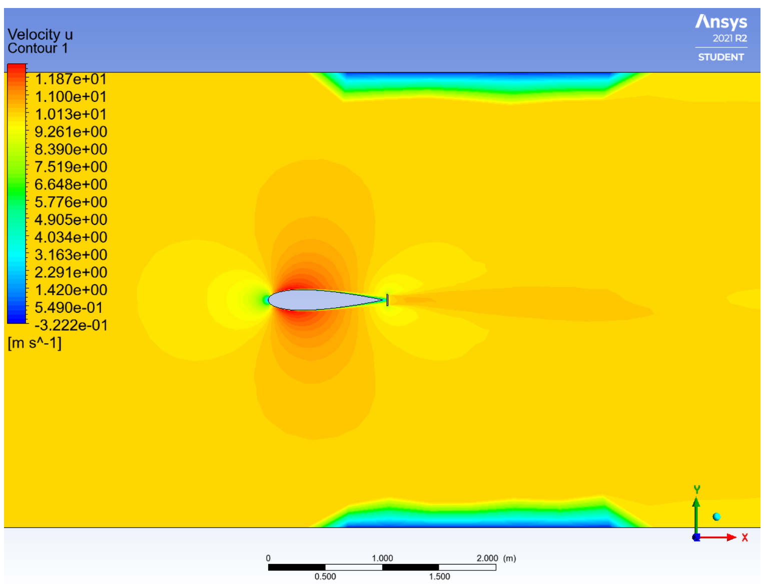

Fig. 7 Velocity Contour for Ideal BLI condition (with actuator disk)

A decrease in mass flow rate of the incoming flow is noted, that evaluates to 4.64% reduction for the BLI configuration. This is due to the decrease in velocity upstream of the propulsor (due to ingestion). Reduced mass flow rate addresses the global aim of reduced level of noise during operation and shaft power.

Overall, the BLI benefit reaches 34.01% compared to the baseline configuration. This quantifies the benefits associated with boundary layer ingestion.

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VII. Conclusion and Future Work

In this paper, the concept of boundary layer ingestion through airframe and propulsion system integration is explained. The benefits associated with this interaction are demonstrated through a prelimanary CFD analysis.

This analysis provides a framework for the further studies in BLI impact on flight performance. Airfoil and actuator disc integration is employed for the study, making up the two configuations; freestream propulsor case and ideal BLI case. When analysed and compared, BLI case is found to have 34.01% less power requirement than the baseline case. Propulsive efficiency for ideal BLI is quantified as 100.51% (greater than freestream propulsive efficiency of 97.41%).

It can be noted from this study that BLI accounts for fuel burn reduction. Therefore, BLI along with synergistic design concept relates global aviation environmental goal by improvement in energy costs, efficiency, community noise and reliability.

Further exploration and study of this concept considers performance parameters in actual flight conditions, viscous effects and losses. Research on mitigating limiting effects of BLI fan like fan distortion, degradation of inlet performance (separation and secondary flows), operability issues and advanced framework for a more integrated design will account for in depth study and efficient implementation of boundary layer ingestion.

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