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2D Numerical Investigation of Boundary Layer Ingestion Propulsor on Airfoil

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Abstract

Imposing a propulsor behind a body can make use of its disturbed flow by decreasing the velocity of air entering the propulsor to save energy and increase the propulsive efficiency since a propulsor consumes less power if the incoming velocity is less. In this article, investigation is conducted on a propeller placed aft an airfoil where it is placed in the boundary layer of the airfoil. This research is conducted to stand on the benefits and drawbacks of this configuration and investigate the mutual interaction between the propeller and airfoil. This interaction is measured by the impact on the power consumption and efficiency, airfoil characteristics, and boundary layer properties.

1. Introduction

From the prospective of reducing power consumption and saving fuel of aircrafts to save the environment a global trend is found lead by ACARE[12] and NASA[10] to reduce fuel consumption to 70% by 2035 and carbon dioxide emissions 75% by 2050. Lately the rate of fuel saving is decreasing because the current power plants has reached high level of efficiency and further development will not be so vital. As an alternative, Instead of enhancing the current engines to meet these requirements, developing of new trends in engines can be more promising to achieve the economic benefits and environmental regulations. One promising solution is to integrate the power plant with the airframe and use the distributed propulsion system, especially Hybrid Turbo Electric Propulsion System.[7] Despite its drawbacks of effecting the flow around the airframe, it can save power by making use of the boundary layer and the wake of the aircraft. By using big number of small sized propulsors immersed in the boundary layer of the airframe, several advantages can be achieved as power reduction and propulsive efficiency increment. Consequently, which leads to reduction in fuel consumption. Also it has better performance in acoustic noise.[3]

The general concept of this propulsion system is that a big numbers of fans distributed along the body are placed inside its boundary layer which allows to get benefit of Boundary Layer Ingestion. These fans are operated by superconducting motor which is linked to a generator by means of superconducting transmission system. To generate electricity, the generators are coupled with a turboshaft engine which is operated on the free stream.[8] A schematic view for aircraft with hybrid turbo electric propulsion system and its block diagram is presented in Figure 1.

Advantages of this propulsion system is numerous.[7] One aim of this propulsion system is to uncouple the fan and the main core of the gas generator. This leads to operate both of them with their optimum velocity individually to get higher efficiency. Also to replace the mechanical link between the main shaft and the fan by superconducting electric components which have higher efficiency and provide more freedom to place the fan away of the gas generator. Several advantages of this system can be achieved as easier maintenance, safe operations in case of one engine failure, higher rotation speeds for propulsors. Moreover, this will allow using small propellers with lower pressure ratio, which perform better in noise reduction.

Boundary layer ingestion (BLI) means taking boundary layer of a body through a propulsor to improve fuel efficiency. The benefit of boundary layer ingestion comes from the fact that re-energizing the aircraft wake needs less kinetic energy than accelerating the free stream air flow. For a fixed thrust, propeller consumes less power if the incoming

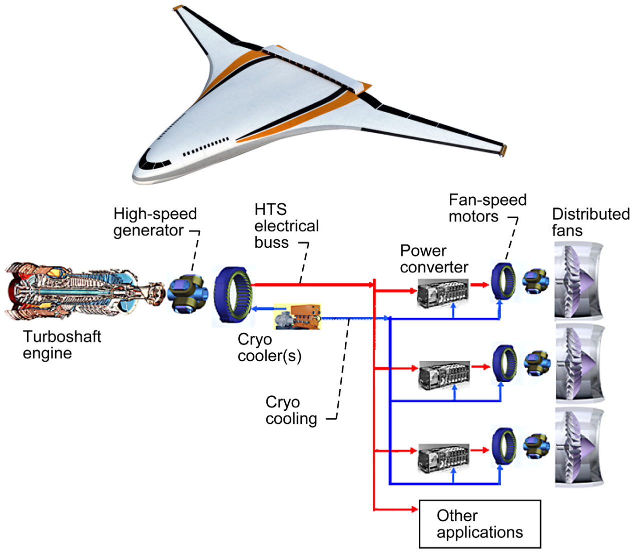

Figure 1: Aircraft provided with hybrid turbo electric propulsion system and its block diagram

velocity is less. Imposing a small propeller in the boundary layer of a body reduces the velocity of air entering the propeller to achieve power saving and increase the propulsive efficiency. Although the benefit of the concept of Boundary Layer Ingestion (BLI) is maximum for axisymmetric bodies, there are another configurations have non-axisymmetric bodies as lifting body and flying wing. From here arises the following question: how the propulsor will interact with the body from the point of view of lift, drag, power consumption, and propulsive efficiency.

Integration between propulsor and a body was studied theoretically in many papers. Smith[17] proved analytically that for the case of a flat plate, propulsive efficiency working on the wake of a flat plate is 127% and power saving about 20%. Teperin and Ujuhu of TsAGI[18] investigated the effect of interference with propeller glider aircraft without considering viscosity. Later, a similar problem has been solved numerically for a propeller mounted at the stern of an airship.[16] In[13] the useful interference between free stream propeller and wing is considered in more detail. Recently, Teperin et al.[19] considered the optimal pressure difference distribution across the propeller to decrease power consumption, and the results shown that the power saving reached more than 20% in comparison of propeller with uniform pressure difference. Drela of MIT[5] derived an analysis of compressible viscous flow around a body with engine based on the mechanical power and kinetic energy instead of the regular forces and momentum flow method, and he explained how to quantify the boundary layer and wake ingestion benefits.

Many experiments were carried out on several bodies as airships where Stern-mounted propellers were investigated as a way to improve the propeller efficiency very much and reduce its power consumption, but they are directed towards airships and large aircraft. In the experiment of McLemore of NASA[15] they achieved propulsive efficiency of 103%. Goldschmit of NASA[9] found that 50% of power could be saved using BLI and counter rotating propellers as in the experimental aircraft Douglas XB-42 Mixmaster.

Concerning the current development for the future aircrafts, the conceptual project of Double Bubble (D8) of MIT, NASA, and Boeing[4] has fuel saving of 33% compared to the optimized conventional configuration having the same technology level using BLI and another techniques. ONERA[2] also achieved 23% of power saving in wind tunnel experiments for a similar project with Airbus.

The interaction between a propeller and a lifting body has both benefits and drawbacks.[11]The advantages on power consumption can be explained using by Froude model of propeller. For the same thrust, the propeller consumes less power if the incoming flow velocity is less. By imposing the propeller in a boundary layer or a wake of a body, the incoming flow will have less velocity compared to the free stream, so the power decreases and propulsive efficiency increases. Efficiency can even exceed 100% since the reference velocity is the free stream velocity which is higher than the actual incoming velocity to the propeller. Another useful point is that the power is a function of the difference between inlet and outlet velocities squared, this counted as a benefit for the power reduction since the incoming flow is not uniform, so the exit velocity can be shaped to give the minimum power consumption.[19]

On the other hand, imposing a propeller in the vicinity of an airfoil will affect the boundary layer and the pressure distribution. Air suction near the trailing edge will create low pressure zone and so the pressure drag on the airfoil will increase and the flow will accelerate. Flow acceleration will increase the shear force and so the friction drag will increase. Also the angle of attack must increase to compensate the losses of lift, which also will increases drag.

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Regarding the effects on the boundary layer and the laminar-turbulent transition, this region will be shifted downstream due to presence of negative pressure gradient zone near the trailing edge, and hence, drag will decrease, but this effect is negligible compared the increment of friction drag due to flow acceleration. Some numerical investigations made by Lutz T. et al.[14] using panel method combined with integral boundary layer equations found that BLI propulsor under some considerations can prevent boundary layer separation.

It is well known that the wake ingestion can be maximized if it operates on a body of revolution because the generated wake is circular exactly like the propeller. However, there are several configurations that do not have well-defined fuselage as a body of revolution, as Blended Wing Body and flying Wings as well as many modern concepts for future aircraft which have usually an airfoil shape.[6] Also, the wake generated behind the wing has bigger area than the fuselage, which is beneficial for the Distributed Propulsion Systems. This motivated the authors to investigate how the propeller located in the vicinity of the trailing edge of an airfoil will impact the power and efficiency of propulsion and aerodynamic characteristics of the airfoil.

This article contributes to the research on distributed propulsion and Boundary Layer Ingestion by considering the integration between an airfoil and BLI propulsor and their mutual effects on the drag, boundary layer properties, propulsive efficiency, and power. It answers three main questions: is it advantageous or not to integrate them from the power consumption point of view, what is the impact on the airfoil performance, and how the pressure and friction drag will be affected.

In order to have deeper look on the interaction between the propulsor and the airfoil this article investigate the lift, drag, and BL properties by comparing the airfoil with and without the propulsor at constant angle of attack. From the point of view of the propulsor parameters (efficiency, power saving â¦) a comparison is made between free stream propulsor and propulsor integrated to an airfoil with mutual interaction under the steady flight condition where thrust is equal to drag.

In this article, for understanding the physical meaning behind the concept of BLI and its benefits a theoretical explanation is presented in Section 2. In Section 3 calculations are conducted for drag and boundary layer properties of the clean airfoil and airfoil with the BLI propeller, power required to overcome the drag by means of free stream and BLI propellers To understand the complex interaction between the airfoil and the propulsor Section 4 discusses the results of the influence of the airfoil on the propulsor and the influence of the propulsor on the airfoil.

2. Theoretical Approach

2.1 Free stream propeller

Froude model can be used for modelling the free stream 2-D propeller – shown in Figure 2– where the propeller is a zero-thickness disk that creates pressure difference converted at the far field to velocity difference producing thrust. The flow is assumed to be axisymmetric, inviscid, without mixing at the jet edges. Thrust is calculated by the following integration[1] :

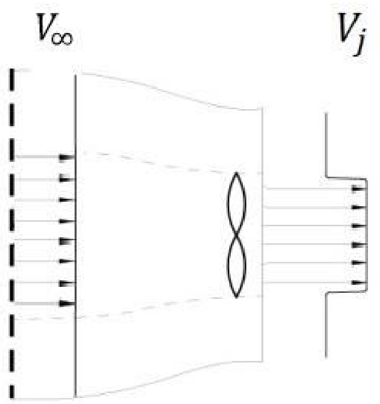

Figure 2: Constant inlet conditions for propeller

$$T = \iint \rho * V_j * (V_j - V_\infty) dA \tag{1}$$

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[1] It is notable that all of the integrations in this section are made on Trefftz plane where pressure is equal to the undisturbed upstream pressure.

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For constant parameters this integration leads to

$$T = \dot{m} * (V_j - V_\infty) \tag{2}$$

Propulsive power added is the difference between the kinetic energies of the stream tube passes by the propeller downstream and upstream the propeller, it is calculated as

$$P_p = \iint \frac{1}{2} * \rho * V_j * (V_j^2 - V_\infty^2))dA \tag{3}$$

and for constant parameters this integration leads to

$$P_p = \frac{\dot{m}}{2} * (V_j^2 - V_\infty^2) \tag{4}$$

The propulsive total power (Equation 3) can be decomposed by the Power Balance Method[5] into two categories: thrust power useful power which is represented by multiplication of thrust by the incoming velocity Equation 5 and wake power due to the velocity perturbations downstream. This wake requires excess energy to be flattened by the flow viscosity. This power is directly proportional to the velocity difference as shown in Equation 6.

$$T * V_\infty = \iint \rho * V_j * V_\infty * (V_j - V_\infty)dA \tag{5}$$

$$E_{wake,prop} = \iint \frac{1}{2} * \rho * V_j * (V_j - V_\infty)^2 dA \tag{6}$$

Propulsive efficiency is defined as the useful power thrust multiply velocity divided by propulsive power (total power). By some mathematics one get the well-known Froude formula

$$\eta = \frac{2 * V_\infty}{V_j + V_\infty} \tag{7}$$

And considering the power decomposition we get

$$\eta = \frac{T * V_\infty}{T * V_\infty + E_{wake,prop}} \tag{8}$$

which can be simply written as:

$$\eta = \frac{D * V_\infty}{E_{prop}} \tag{9}$$

It is notable that the actual power is more than the calculated power because of the viscous and induced losses.

2.2 Drag Characteristics

Drag is the momentum losses between upstream and downstream flows of a stream tube passes around a body according to the momentum equation[1] as shown in Figure 3. Therefore, it can be calculated directly from the velocity distribution of the wake by the following formula

$$D = \iint \rho * V_w * (V_w - V_\infty)dA \tag{10}$$

This force can be represented in form of power consumed as drag multiplied by the upstream velocity

$$D * V_\infty = \iint \rho * V_w * V_\infty * (V_w - V_\infty)dA \tag{11}$$

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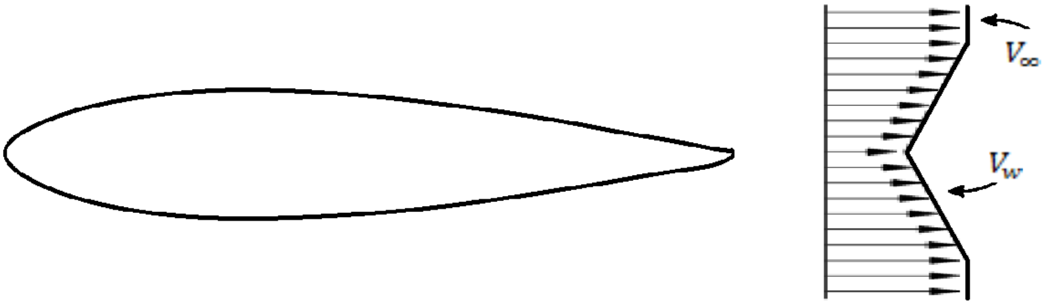

Figure 3: Airfoil and velocity distribution of the wake.

This power is consumed due to two reasons: dissipation in the viscous boundary layer and velocity perturbation in the wake. The dissipated energy in the boundary layer is quantified as the energy losses between upstream and downstream in the stream tube that passes around the airfoil, which is equal to

$$\phi_{BL} = \iint \frac{1}{2} * \rho * V_w * (V_\infty^2 - V_w^2))dA \tag{12}$$

While the energy of the wake can be quantified by the perturbations in the stream tube and calculated by the following equation:

$$E_{wake,prop} = \iint \frac{1}{2} * \rho * V_w * (V_\infty - V_w)^2 dA \tag{13}$$

And hence, the total consumption in kinetic energy is the summation of the BL dissipation and the wake perturbations which are equal to the drag power

$$D * V_\infty = E_{wake,prop} + \phi_{BL} \tag{14}$$

2.3 Ideal BLI Propulsor

The concept of the ideal Boundary Layer Ingestion Propulsor is to make use of the BL air and reenergize it to generate the same amount of thrust but by less power. In addition, the BLI propulsor will "fill" the momentum gap generated by the body due to drag and so it will minimize the wakes created by the body and the propeller downstream which will decrease the losses in kinetic energy very much as shown in Figure 4. Moreover, the free stream propulsor obtain thrust by accelerating the free stream which will generate propulsor wake downstream which absorbs energy too.

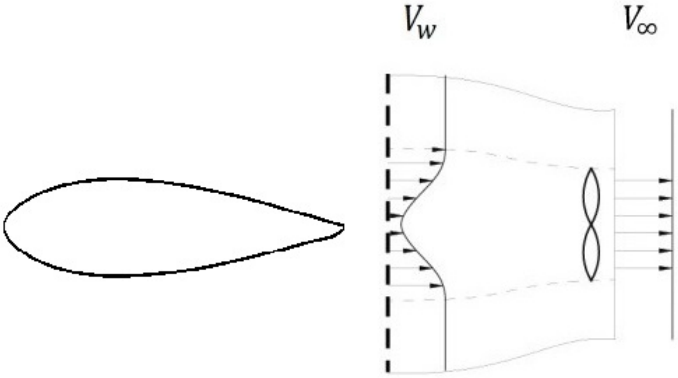

Figure 4: Perfect boundary layer Ingestion.

In the ideal case, all the wake will be ingested and flattened, the jet velocity will exactly match the undisturbed velocity. Thus, the only energy dissipated will be due to the BL viscosity which is defined by Equation 12. Since the stream

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tube is accelerated to the upstream conditions and all the wake is eliminated, the kinetic energy added by the propulsor to the stream tube will be equal only to the losses in the boundary layer, which can be evaluated as the difference in kinetic energy of the flow in front of and behind the body as in the following equation:

$$E_{prop,BLI} = \iint \frac{1}{2} * \rho * V_w * (V_\infty^2 - V_w^2) dA \tag{15}$$

So the required power decreased while the drag and thrust still exist with the same value.
One main important parameter used to quantify the benefit of BLI is the power saving coefficient which is defined as in the following equation

$$PSC = \frac{P_{noBLI} - P_{BLI}}{P_{BLI}} \tag{16}$$

Concerning the efficiency of this system, the propulsive efficiency is still defined as the useful power (thrust multiply velocity) divided by total power. Since trust is equal to drag, we can replace the numerator to be $D \times V_\infty$. By using Equation 14 the efficiency in will be

$$\eta = \frac{D \times V_\infty}{E_{prop,BLI}} = \frac{\phi_{BL} + E_{wake,prop}}{\phi_{BL}} > 1 \tag{17}$$

3. Calculations

3.1 Problem Description

Supercritical Whitcomb airfoil is used with chord of 1 m. Lift coefficient is set to be 0.5, Mach number of the incoming flow is 0.79 which corresponds to the design point of the airfoil. Ambient pressure is 1 atmospheric pressure and the ambient temperature is 216.6 ^{o}K. Reynolds number based on the inlet velocity and the airfoil chord is 2.11×10^7.

3.1.1 Mesh Description

Rectangular domain of size of 10×10 m with thickness of 0.01 m is used. The airfoil is placed 4 m apart from the domain inlet and 5 m apart from the upper limit of the domain. Airfoil has element size of 0.01 m. Element size in the body of influence is 0.05. structured mesh is constructed around the airfoil by 12 layers with growth rate of 1.3. Unstructured mesh is constructed with total number of elements of 250 thousand elements. Simulations are computed using Ansys CFX using RANS equations and Shear Stress Transport (SST) turbulence model.

3.1.2 Boundary Conditions

Boundary conditions are critical for the physical interpretation and to ensure solution stability. The boundary condition on the airfoil is no-slip wall. All boundary conditions are listed in Table 1.

Table 1: Boundary conditions for the domain

Surface	**Boundary Condition**
Domain Inlet	Subsonic velocity inlet, Medium Turbulence Intensity
Domain Outlet	Opening, zero gauge pressure
Domain sides	Symmetry
Airfoil	No slip, smooth wall with Adiabatic heat transfer

Calculations are done at angle of attack of 0.519^{o} which corresponds to lift coefficient of 0.5, drag coefficient is found to be 0.01247. Drag coefficient is decomposed to pressure drag of 4.27e-3 and viscous drag of 8.2e-3. Mach number contour is shown in Figure 5.
Considering the boundary layer definition, it is defined herein that the boundary layer is the region where the velocity is less than 99% of the far field undisturbed velocity. According to that definition, the boundary layer for the upper airfoil surface has thickness of 0.028 m but the lower thickness is not concerned because it is affected by the high pressure field in the downside of the airfoil. Displacement thickness is 6.59e-3 m, momentum thickness is 3.96e-3 m, energy thickness is 6.53e-3 m, and the shape factor is 1.663.

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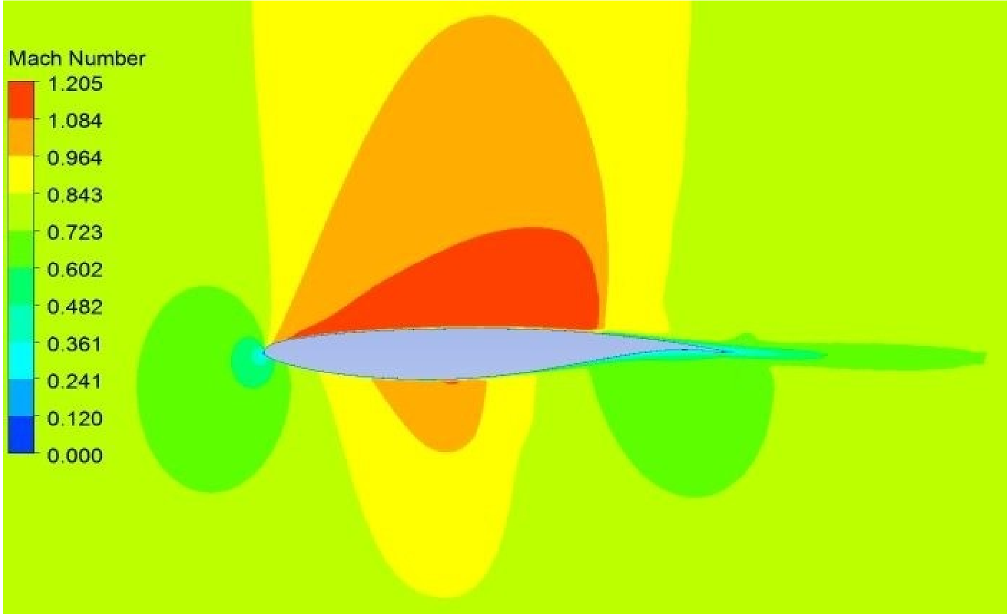

Figure 5: Mach contour around the airfoil.

3.2 Free-Stream Propulsor

Thrust is set to be equal to the profile drag (5.617 N). Using the uniform free stream air as inlet condition to the propulsor of diameter 0.1 m, CFD calculations are carried out. Efficiency is calculated by dividing the thrust power on the propulsive power or simply by using the velocities upstream and downstream as in Equation 9. The results show that mass flow rate= 0.402 kg/s, Power required = 1585.88 W, and the propulsive efficiency= 0.809.

3.3 BLI Propulsor

The case of propulsor placed behind an airfoil is simulated, and the propeller is modelled using active disk theory with diameter of 0.1 m, which corresponds to 10% of chord, placed 0.04 m behind the trailing edge of the airfoil which corresponds to 4% of chord.

To ensure perfect reenergizing of the boundary layer the boundary conditions of the propulsor were set to have mass flow rate inlet boundary condition to provide the required thrust calculated by Equation 18

$$\dot{m_{T,i}} = \dot{m_{T,i-1}} + \frac{D-T}{S_{prop}} \times K \tag{18}$$

where $\dot{m_{T,i}}$ and $\dot{m_{T,i-1}}$ are the mass flow rates in the previous and current iterations, S_{prop} is the propulsor area and K is a relaxation factor. Velocity outlet boundary condition is used to ensure the mass flow conservation by means of Equation 19

$$v_{out} = \frac{\dot{m}}{S_{prop} \times \rho_{out}} \tag{19}$$

where v_{out} and ρ_{out} are the velocity and density at the propeller outlet.

Concerning the airfoil total coefficients, to achieve lift coefficient of 0.5 angle of attack increased to 0.69^o and the drag coefficient is 0.01557. Pressure component of the drag is 6.97e-3 while the viscous component is 8.6e-3. Mach number contour is presented in Figure 6.

Considering the impact of the propeller on the boundary layer properties, the boundary layer upper limit became 0.025 m. Displacement thickness is 4.96e-3 m, momentum thickness is 2.97e-3 m, energy thickness is 5.05e-3 m, and the shape factor is 1.669.

It is noticed that drag increased due to the effect of the propulsor and, consequently, thrust increased but the power decreased because the propeller ingests slower air than the ambient. Total thrust and power are 7.01 N and 1392.35 W respectively and efficiency is 1.173 and mass flow rate is 0.346 kg/s.

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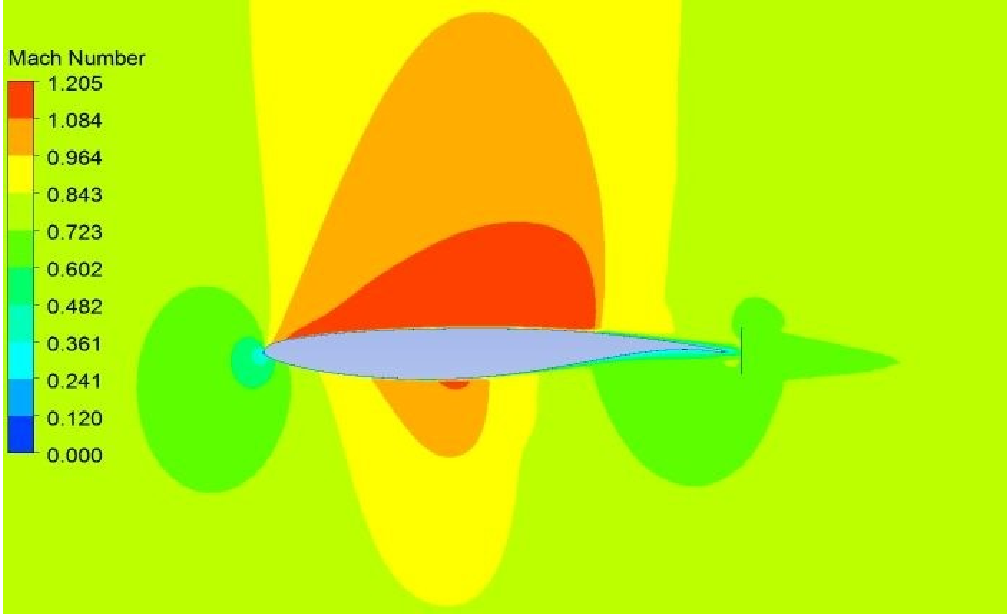

Figure 6: Mach contour around the airfoil – propeller configuration.

4. Results and Discussion

4.1 Influence of the Airfoil on the Propulsor

The main effect of the airfoil on the propulsor is that the propulsor will ingest slower air and reenergize the wakes downstream the airfoil. This will have a favorable influence on the power and efficiency. Power saving for this case as calculated from equation 16 reached 12.203% compared to the propeller of the same size ingests free stream air. Efficiency became 1.117 compared to 0.809 for the free stream case. Mass flow rate decreased 13.93% which means that the propulsor can operate with reduced level of noise and shaft power. On the other hand, the propeller has to increase its thrust to satisfy the steady flight condition where thrust equals drag of the airfoil. The results are summarized in Table 2.

Table 2: Comparison Between the Different Types of the Propulsor

Property	**Free Stream Propulsor**	**BLI Propulsor**
Thrust [N]	5.617	7.005
Power [W]	1585.88	1392.35
propulsive Efficiency	80.90%	117.30%
Mass Flow Rate [kg/s]	0.402	0.346
Power Saving	–	12.20%

4.2 Influence of the Propulsor on the Airfoil

The propulsor acts as a negative pressure gradient zone behind the airfoil and this will have a severe effect on the airfoil characteristics. The propeller will accelerate the flow not only over but also under the airfoil which leads to reduce the pressure difference across the airfoil and lift will decrease. To compensate this reduction in lift angle of attack increased which, consequently, increases the drag because the projected area facing the flow increased. By analysis of the pressure distribution around the airfoil, it is noticed that Pressure field is not affected by the presence of the propeller in the first 40% of the chord as shown in Figure 7. BLI configuration shifted the shock wave of the upper airfoil surface upstream. In the maximum thickness position in the lower surface has higher velocity which has unfavorable effect on lift. This reduction is compensated near the trailing edge of the upper surface but on the other hand increases pressure difference between leading and trailing edges. It is noticeable that the pressure polar of the BLI configuration is shifted upwards which means more drag is faced.

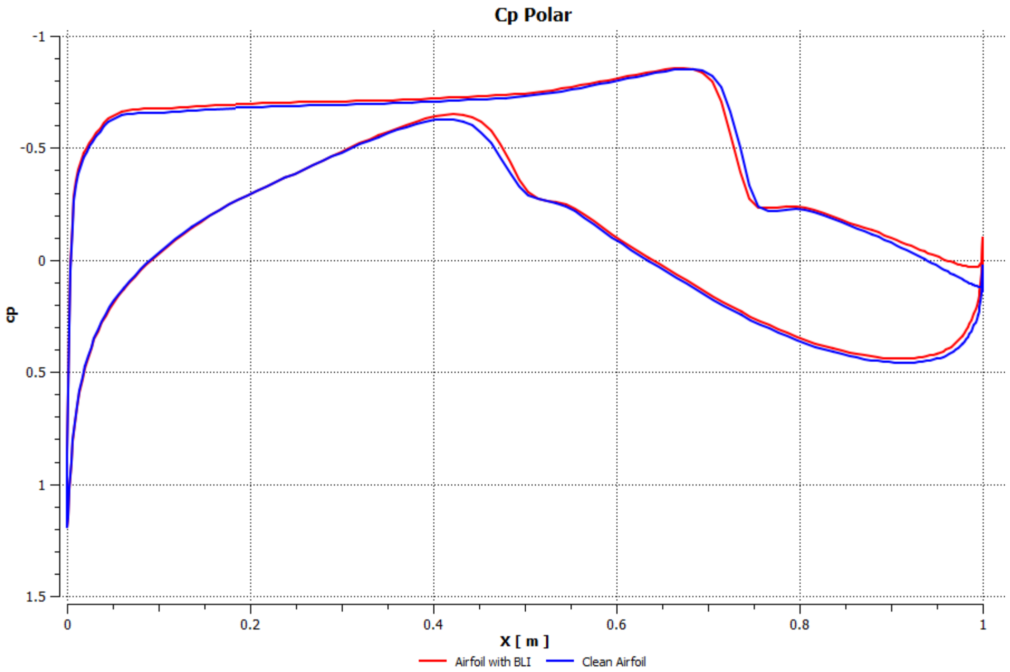

Figure 7: Pressure coefficient distribution around the airfoil with and without propeller interaction.

Drag can be divided into two independent reasons, pressure and viscosity terms. Presence of a propeller in the vicinity of the trailing edge changed the pressure field around the airfoil by increasing the pressure difference between leading and trailing edges which is depicted in pressure drag increment of 63.23% compared to the clean case. Since the flow is accelerated around the airfoil more friction is applied on its surface. Results show that this increment is 4.88% which rather small and can be neglected with respect to the pressure drag increment. Boundary layer characteristics can provide better understanding of viscosity effects. The BL upper limit became 0.025 m with reduction 10.71%. This proves that BLI stabilizes the flow around the bodies. Displacement decreased 24.73%, momentum thickness decreased 25%, and energy thickness decreased 22.66% which indicate that BLI has less losses due to viscosity compared to the clean case. The shape Factor increased 0.36% which means that the flow turbulence is reduced slightly and BLI helps in stabilizing the boundary layer. These results are summed up in Table 3.

Table 3: Properties of the airfoil with and without the propulsor

Property	**Airfoil Alone**	**Airfoil with Interaction**
Lift coefficient	0.5	0.5
Angle of attack [deg]	0.519	0.69
Drag coefficient	0.01247	0.01557
Pressure drag coefficient	4.27E-03	6.97E-03
Friction drag coefficient	8.20E-03	8.60E-03
BL upper limit [m]	0.028	0.025
Displacement thickness [m]	6.59E-03	4.96E-03
Momentum thickness [m]	3.96E-03	2.97E-03
Energy thickness [m]	6.53E-03	5.05E-03
Shape factor	1.663	1.669

Despite of the fact that the drag increased 24.86% the consumed power decreased 12.2%. This leads to conclude that the drag is not a proper indicator for the aircraft economical representation and it is better to use the power since it is directly related to the fuel consumption.

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5. Conclusion

Comparison between airfoil with and without Boundary Layer Ingestion (BLI) propeller is conducted to criticize its benefits from view point of power and efficiency and to get a closer look on the mutual interaction between them. This interaction is measured by the impact on the power consumption and efficiency, boundary layer properties, and airfoil characteristics. Investigations show that although BLI configuration decreases left and increases drag, consumed power decreases since the propeller ingests slower air. Drag increased for the given flight conditions 24%, friction drag increased 5% and 63% for pressure drag compared to the clean airfoil case which depicts that the main effect of the BLI interaction is on the pressure-dependent parameters. On the other hand, the power is reduced by 12% and hence it is useful to use the boundary layer ingestion propulsor from the viewpoint of power saving. Moreover, BLI stabilizes the boundary layer and tends to decrease its turbulence.

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