AFT-MOUNTED BOUNDARY LAYER INGESTING PROPULSORS: THE NEXT STEP IN AIRPLANE EFFICIENCY

Nathan Kueppel (nak140@pitt.edu), Mahboobin 10:00, Jacob Frye, (jafl84@pitt.edu), Vidic 2:00

Abstract - Airlines and aeronautical engineers are constantly searching to increase the fuel efficiencies of aircraft to save on fuel costs and improve design sustainability. Current improvements look to use lighter materials in the aircraft frame, such as carbon fiber, to reduce the amount of thrust necessary for flight. Such improvements are costly in terms of the materials necessary, and provide only incremental increases to efficiencies. The use of boundary layer ingesting (BLI) propulsion promises much larger increases to design efficiency. BLI propulsion involves placing the turbofans of the aircraft, which provide thrust, into the region of slower moving air directly above the fuselage, or body, of the plane, which increases intake air pressure, and, by extension, the propulsive efficiency. The use of this technology is currently being researched by the Massachusetts Institute of Technology (MIT) and National Air and Space Administration (NASA) for use in the D8 “double bubble” aircraft, which seeks to meet aggressive fuel burn reduction goals set by NASA for aircraft poised to enter service by 2035.

Key Words - Aeronautics, Aircraft Innovation, Boundary Layer, D8 “Double Bubble,” Jet Propulsion, Massachusetts Institute of Technology, National Air and Space Administration

THE BASIS FOR AERONAUTIC INNOVATION

The designs of aircraft are constantly evolving to become faster, more comfortable, and more efficient. This has the advantage of not only decreasing operating costs for airlines from fuel, but also increasing public perception of the airline industry as companies dedicated to both their customer and the environment. According to an article by Thom Patterson, senior producer and aviation reporter for CNN, aircraft manufacturers are continuing this trend. He describes five of the newest aircraft at the 2016 Farnborough International Airshow in Farnborough, England as largely using carbon fiber designs and wider cabins to make planes lighter, more fuel-efficient, and more comfortable [1]. While using carbon fiber to build planes makes for a lighter design that can save fuel, it is very expensive compared to traditional materials. This makes the economic sustainability of these designs questionable.

In a related vein to increasing fuel efficiency, NASA has challenged aircraft manufacturers to go a step further. NASA has set aggressive goals for reducing total flight fuel burn, as well as noise generated and takeoff distance required, hoping to achieve these objectives by the year 2035, per a paper by Ashcraft, Padron, Pascioni, Stout Jr, and Huff, researchers at the NASA Langley Research Center [2]. Looking to propulsion for the solution instead of material use, there is a technology that has not been focused on as much that promises to meet these goals, at a lower cost. Boundary layer ingesting (BLI) propulsion, currently being researched by MIT and NASA for use in the D8 “double bubble” aircraft, stands poised to increase propulsive efficiency over traditional free-stream podded turbofans, and thus lead to decreased fuel consumption during flights.

THE STATE OF JET PROPULSION TODAY

Development Of The Jet Engine

To discuss the advantages of boundary layer ingesting propulsors, it is useful to have background information on what the propulsion system in commercial aircraft is, and how it functions. Aircraft propulsion has evolved over the past 70 years from propellers, to jet engines, and then to the modern turbofan. Jet engines and turbofans are the two propulsion systems largely in use today, and while largely similar, contain efficiency differences that make turbofans more suitable for use with boundary layer propulsion. Knowing how each provides thrust proves this point.

In literature, the term power plant is used to refer to the engine of any air craft. Both a small Cessna flying overhead and a large Boeing 747 rely on their power plants for thrust, but the mechanism by which thrust is produced differs. The standard private or personal aircraft, relies on an engine rotating a crank shaft, which drives a propeller [3]. This practice dates to the Wright Brothers, and has been one of the oldest methods of propelling an aircraft. Until March 25, 1942, around the end of WWII, all aircraft were built with prop engines. On this date, the Germans successfully flew the Messerschmitt 262 Aircraft, the first of its kind to rely on a new technology – jet engines, as described by former Director

The jet engine overcame a vital flaw that was faced at the time by propeller engines; around a blade speed of Mach 1, the speed of sound, the propeller would grow inefficient [3]. This inefficiency would reduce the overall speed attainable by the aircraft, which in turn limits other design constraints such as wing shape, airfoil, and body design. The invention and application of jet engines surpassed this constraint.

A Breakdown Of Jet Engine Operation

The jet engine can be broken into four phases: intake, compression, combustion, and exhaust [3]. During the intake phase, air moving in front of the aircraft flows into the jet engine, where it reaches the compression phase. Here, a series of moving and stationary fan blades slow the intake air, thus raising its pressure, an explanation of which will come in the next section. Note that it will be discussed later what powers the moving fans in the compression phase. After the compression phase, the air moves towards the combustion phase, where it is mixed with fuel and ignited [3]. Once ignited, the burned fuel and air mix, called exhaust, moves through a series of fans behind the combustion phase. The fans through which the exhaust moves are on a central axle with the fans in the compression phase. The engine contributes to its own efficiency by using its exhaust to slow down and burn more of the air going into the engine [3]. The exhaust, after moving through the rear fan blades, exits the engine at high speeds and pushes the aircraft forward via newton’s third law of physics; as the gas is forced backwards, the plane moves forward. This was a revolutionary idea which allowed the aircraft to travel at much higher speeds.

![Turbojet Engine](image)

FIGURE 1 [3]
Components of a jet engine

An Overview of Turbofan Components

After the development of the jet engine, the next innovation to aircraft propulsion was the turbofan. Due to its prevalence in current aircraft, the term propulsor is often used interchangeably with turbofan, due to the turbofan being the source of propulsion, the root of propulsor, for the aircraft. The turbofan differs from the jet engine due to the addition of large, fan-like blades at the front of the jet engine. Turbofans are now favored over jet engines, and have a slightly different mechanism for providing thrust.

Mentioned previously, jet engines have compressor fans on an axle which runs through the center of the engine. The force of heated exhaust passing over additional fan blades in the rear of the engine drives this axle. In a turbofan engine, a large fan blade is added to the axle in the front of the engine. The fan blade has a radius much larger than that of the jet engine it is attached to. When the fan blade spins, it forces some air into the engine, while most of the air flows around the engine, skipping all phases of compression and combustion, until it is pushed out of the back of the engine with the exhaust, contributing to the thrust. This makes the turbofan engine more efficient as it uses the excess energy from its exhaust to create more thrust and further contribute to its own intake cycle. Describing a turbofan is typically done in regards to its bypass ratio.

The bypass ratio, per Loftin’s book, “is defined as the ratio of the mass of air that passes through the fan, but not the gas generator, to that which does pass through the gas generator” [3]. Essentially, the higher a turbofan’s bypass ratio is, the more air merely flows around the engine instead of being combusted. When the air flows around the engine, it is not wasted, it instead boosts the thrust of the engine, as the fan acts in a similar vein to a propeller. Whereas the jet engine uses its exhaust only to help pressurize its intake, the turbofan uses its exhaust to pressurize its intake, power a thrust-producing fan, and cool itself in the process. High bypass ratio turbofans are the giant engine pods seen on the wings of international airliners, while low bypass ratio turbofan engines have smaller cross sectional areas than their counter parts, making for more compact additions to aircraft.

Turbofans prove themselves to be superior to jet fans when considering implementation into boundary layer systems. A jet engine relies on its combustion to power its compressors, as well as propel the aircraft through the air. When the air in front of the jet engine is too slow; however, the jet engine is not as effective. A turbofan uses its exhaust to not only generate more thrust from the fan, but to also feed more air into the engine. This allows the turbofan to function when intaking slow-moving air from the boundary layer, as it can force air into the engine and produce thrust. It is this quality of turbofan engines that makes them ideal for designs seeking to implement BLI propulsion, such as the D8 “Double Bubble” aircraft from MIT. Having described the propulsion element of boundary layer ingesting propulsion, the concepts of fluid flow and the boundary layer itself must be addressed.
Before discussing boundary layer ingesting (BLI) propulsion, it is important to introduce the concepts of fluid flow over a surface, and the boundary layer itself, allowing for an understanding of how the technology works, as well as some of the barriers it faces. The primary source for information regarding fluid flow and the boundary layer comes from Dr. Sung Kwon Cho, Associate Professor in the Department of Mechanical Engineering & Materials Science in the Swanson School of Engineering at the University of Pittsburgh, and instructor of Applied Fluid Mechanics. The boundary layer refers to the section of air above a solid body that flows at a velocity less than that of free-flowing air. The reduction in velocity is due to friction between the air molecules and the molecules of an unmoving surface, in this case the airplane fuselage. The frame of reference for discussing boundary layer air flow is that the fuselage is not moving, and the air is. Per the Law of Conservation of Energy, the initial kinetic energy, energy from motion, of the air must be equal to the sum of the final kinetic energy and the energy lost to friction. Therefore, the presence of friction necessitates a loss of kinetic energy, and thus a loss of velocity, to compensate. The air directly above the fuselage has a velocity approaching zero due to high amounts of friction, which is called the no-slip condition. The air slightly above the no-slip condition has a higher velocity, due to friction occurring between air molecules only, not air and the fuselage. The further away from the fuselage the air is, the closer its velocity comes to that of free-flowing air. The decreased air velocity contributes to greater propulsive efficiency.

**AIR FLOW OVER A BODY AND THE BOUNDARY LAYER**

**Defining The Boundary Layer**

BLI propulsors increase efficiency because slower moving air exerts a greater pressure, or force per unit area. The relationship between velocity and pressure of a fluid is given by Bernoulli’s equation: $P_1 + \left(\frac{\rho V_1^2}{2}\right) = P_2 + \left(\frac{\rho V_2^2}{2}\right)$, where $P$ is the static pressure of the fluid, $\rho$ is the density of the fluid, and $V$ is the velocity of the fluid. One side of the equation represents the boundary layer air, and the other represents free-stream air. Because the same fluid, air, is used for both free-stream air and boundary layer air, the density remains constant, making the static pressure and velocity the only two variables. If we fix the values for free-stream air, one side of the equation, as constant, it has been established that boundary layer air travels at a lower velocity. Therefore, to balance and keep the two sides of the equation equal, the static pressure of the boundary layer air must be greater than that of free-stream air. A higher initial pressure means that the turbofan does not need to generate as much additional pressure in the air to create the same level of thrust as in free-stream air, resulting in energy savings. The application of using the boundary layer to increase efficiency is made difficult, however, due to another characteristic of boundary layer air, the propensity for separation.

**The Problem Of Separation**

In discussion, Dr. Cho stated that when air flows over the initial rise of a curved airfoil, it accelerates to make up for the blockage in its path. This portion of the airfoil is called the accelerating edge. After passing the rising edge of the airfoil, the air then does the opposite, decelerating in response to an increase on the cross-sectional area the air must now occupy, along what is called the decelerating edge. Separation occurs when the air loses too much energy due to
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friction along the accelerating edge and is unable to continue to flow along the contour of the airfoil. This is generally caused when the angle of the wing with respect to the flow of air, a measure called angle of attack, is too large. The air then separates from the airfoil, leaving a region without air along the decelerating edge. To fill in this region, the separated air circles back, creating what is known as a vortex. Vortices are regions of unstable flow, constantly changing size and direction. This distorted air makes for an unreliable source of intake for turbofans, reducing propulsive efficiency, as well as reducing the lift experienced by the plane in general. The combination of the two can result in a plane being rendered incapable of flight should it pitch slightly too far up. Angle of attack is greatest at takeoff, which could render a plane incapable of leaving the ground in the first place. There is a current solution to vortices, called vortex generators, that can increase the angle of attack allowed before stall occurs, at the cost of increasing friction.

The D8 “Double Bubble” aircraft is a design response to an initiative for new aircraft to be built three generations later than current state-of-the-art technology, referred to as the N+3 time period, by NASA. This initiative is described in a paper by Ashcraft, Padron, Pascioni, Stout Jr, and Huff, who are researchers at NASA’s Glenn Research Center. The goals for the initiative are to reduce in-air fuel burn by at least 70%, decrease noise from flight by 71 decibels, and minimize takeoff distance to allow for use of as many runways as possible [2]. The fuselage design combines two traditional fuselages together, creating a body that provides a significant amount of lift, in addition to the wings. The primary benefits of the design come from use of rear-mounted BLI propulsion, “natural laminar flow on the wing bottom, an advanced combustor, composite materials, a lifting nose, and pi-tail,” which allow it to get close to achieving the fuel burn, field length, and noise reduction goals [2]. The focus of this paper will be on the use of the BLI propulsion in the design.

The propulsive efficiency of a turbofan is given in an article by NASA detailing proposed solutions to desired fuel burn, noise, and emission reduction goals for future aircraft design. The equation is: $n_p = 2U_0/(U_f + U_a)$, where $n_p$ is the propulsive efficiency, $U_0$ is the free stream velocity, $U_f$ is the jet exit velocity, and $U_a$ is the inlet velocity [2]. The inlet air velocity and free stream velocity are the same in traditional turbofan use. For boundary layer ingesting turbofans, however, the inlet air velocity is less than the free stream air velocity, as described in the introduction to the boundary layer. This leads to a greater propulsive efficiency for BLI propulsion when compared to traditional propulsion. This equation is a mathematical representation of how the lower
velocity and greater air pressure of the boundary layer air contributes to propulsive efficiency.

According to Science Learning Hub, an educational initiative of the New Zealand government, wake describes a region of low velocity air behind an aircraft that circulates back in towards the body [11]. The turbulence of this air creates a low-pressure zone behind the aircraft. This results in a net force opposing the motion of the aircraft, known as drag. When the turbofans are moved to the aft of the aircraft, the jet exit air is released into the region where wake would typically form, as shown in research conducted by Shishir Pandya, a member of the Applied Modeling & Simulation Branch at the NASA Ames Research Center [12]. This re-energizes and smooths the air behind the aircraft, reducing wake, and thus drag. Because of this reduction in drag, less thrust is needed to maintain the same speed, saving power.

**Experimental Findings**

Experiments analyzing the efficiency increase for the D8 aircraft from utilizing boundary layer ingestion, as opposed to traditional free-stream ingestion, have been carried out by MIT and NASA in the 14-by-22foot subsonic wind tunnel at NASA’s Langley Research Center, using a 1:11 scale model of the proposed D8 design [12]. The experiments validated results using computer modeling, and sought to find the mechanisms for the BLI benefit. The results found a 6% benefit to electrical power and a 9% increase to mechanical flow power, or propulsive efficiency, solely as a result of implementing BLI propulsion. This increase to propulsive efficiency translates almost directly into fuel reduction benefits of the same percent, as stated in a research paper by the American Institute of Aeronautics and Astronautics [13].

**Addressing The N+3 Timeframe**

Defined in the paper by Ashcraft and associates, the N+3 timeframe, under which the D8 aircraft falls, describes designs that exhibit a high, “likelihood of being operational by 2035” [2]. It is important to address how technology intended to be operational in almost twenty years is relevant today. The reason for the N+3 designation is that the technology used in the designs is not currently available. For the D8, this includes the advanced combustor, composite materials, and BLI propulsion. There are currently not turbofans available that maintain efficiency when immersed into turbulent boundary layer air streams, negating the potential benefits to fuel efficiency the technique presents, although it has been indicated that this issue can be overcome [2]. Research into fuselage designs to aid in smooth boundary layer air flow, or turbofans with proper tolerance needs to be conducted for BLI propulsion and the D8 aircraft to become reality. In addition, experimenting with designs that can ingest a greater percentage of the boundary layer has the potential to increase the benefits of BLI propulsion further.

The research conducted at the Langley Research Center has shown small increases in performance for BLI propulsion using current technology. This increase can be capitalized on with a greater focus on the technology.

**THE BENEFITS OF BLI PROPULSION**

BLI propulsion has the potential to drastically change aircraft design if it is successfully implemented. Moving turbofan placement to the aft of the aircraft can be combined with new experimental fuselage and wing designs to find the most efficient aircraft. NASA’s desired specifications for the N+3 generation of aircraft provides incentive for aircraft manufacturers to encourage engineers to experiment with new designs utilizing boundary layer ingestion. This brings potential to the professional engineering field as it would be given room to expand and innovate. The unconventional design of the D8 is one example of how aircraft can adapt to take advantage of new technology. In the D8’s case, innovation has led to a fuselage that acts as a lifting body as well, contributing further to efficiency while looking too maximize the benefits form BLI propulsion. Utilizing boundary layer ingesting propulsion also promotes sustainability of design in economics, innovation, and environment.

**Economic Benefits Of BLI Propulsion**

Economic sustainability describes a design that brings an overall profit in its implementation. If a design can cut carbon dioxide emissions, but adds significantly to the overall cost of production of a product, or to the cost of operating the product, that design is not economically sustainable. The aviation industry brought in $701 billion dollars in global revenue in the year of 2016, and transported 53.9 million tons of freight, as stated in an economic performance report by the International Air Trade Association (IATA) [14]. This field is one that not only impacts many people, but is integrated into the global trade network, and tied into national economies everywhere. Therefore, economic sustainability is of utmost concern when looking to change aircraft designs. The use of BLI propulsion has the potential to allow aviation to continue to aid in the global economy, while decreasing operating costs from fuel consumption.

The primary appeal tied to the D8 aircraft is its projection to reduce fuel consumption markedly. The airline industry spent a total of approximately $124 billion on fuel in 2016, per a fact sheet from the International Air Transport Association [15]. From an economics chart by the IATA, this price represents a 48% increase from the previous year, and about 19% of the operating costs for the industry [15,16]. If one applies the 9% fuel consumption reduction from the D8 testing to this cost, it results in savings of about $11.2 billion per year for the aviation industry. This has the potential to increase the impact aircraft have on the global economies, being freed from a significant cost of operation.
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While a 9% decrease in fuel consumption drops operating costs for airlines, this benefit, unfortunately, does not translate to savings for customers. Joe Pinsker, associate editor for The Atlantic newspaper, reported on this phenomenon in his article “Why is Flying Still Expensive Even Though Fuel’s Gotten So Cheap?” In 2016, jet fuel costs were approximately one-third of what they were in 2014, yet ticket prices only fell about 3 percent per quarter for the year [17]. Pinsker explains that this is due in large part to a lack of competition in the airline industry, which allows for prices to be kept high. So, while it cannot explicitly be forecasted or promised that the D8 or boundary layer ingesting air craft will lower airline prices, it can still be said that aircraft will consume less fuel, and thus provide a net economic benefit when implemented.

Benefits To Aviation

Sustainability of innovation is the idea that a new technology opens possibilities for new designs to come forth, instead of requiring a single design for the technology to function. The tube shape of modern commercial aircraft has changed very little from the first commercial jets, like the Boeing 707, which was commissioned in 1958, per Laurence Loftin’s book on aviation history [18]. This means that for almost the past 60 years there has been very little variability in how the fuselage has been designed. The D8 aircraft shows how introducing BLI propulsion can allow for a different fuselage in the design.

As shown in figure 5, the D8 resembles two traditional fuselages put together. MIT also designed a long-distance aircraft that uses BLI propulsion, called the H-series Hybrid Wing Body, pictured below.

![Computer generated image of the H-Series Hybrid Wing Body](image)

**FIGURE 6 [2]**

**Computer generated image of the H-Series Hybrid Wing Body**

This fuselage design sweeps the wings outward from the fuselage, maintains the aft-mounted turbofans, and does is a very different design from the traditional tube fuselage configuration. As engineers seek to maximize the amount of boundary layer air that is ingested, and smooth out the airflow over the fuselage, there is the potential for a great degree of freedom in design.

Environmental Benefits

For a technology to be environmentally sustainable, it must exert a minimum of negative impacts on nature, either through its consumption of natural resources, or through the pollutants it produces. BLI propulsion is capable of greatly reducing the current impact of aviation on the environment through its fuel burn reduction. Using data from a fuel fact sheet published by the International Air Transportation Association, $124 billion was spent on fuel, at $44.6 per barrel in 2016 [15]. This equates to 2.78 million barrels, or 116 billion gallons, of fuel consumed by the aviation industry. A 9% reduction in fuel burn would therefore result in a savings of 10.5 billion gallons of fuel per year. When considering that fuel is a nonrenewable resource, these are significant savings for natural resources.

Using the economic performance statistical spreadsheet from the IATA, consumption of jet fuel generated 814 million tonnes of carbon dioxide emissions in 2016 [14]. A 9% decrease in fuel burning equates to 73.3 million tonnes of carbon dioxide that will not be produced. In NASA’s design goals for aircraft in service by 2035, they are aiming for a 75% reduction in NOx emissions on takeoff [2]. The United States Environmental Protection Agency specifies NOx as representing nitrogen oxide, which, “plays a major role in the atmospheric reactions with volatile organic compounds (VOC) that produce ozone (smog) on hot summer days” [19]. Reducing these emissions by 75% can help reduce air pollution, especially in larger cities, where air traffic is heaviest and air pollution can be an issue. In recent years, the increased acknowledgement of the responsibility of people to the environment has led to an emphasis on cutting emissions and consumption where possible. As the aeronautic industry plays such a large part in the global economy, and thus is unlikely to go away any time soon, the increased environmental sustainability offered by BLI propulsion helps fulfill these desires.

MOVING FORWARD

Boundary layer ingesting propulsors stand to provide significant benefits to the aeronautic industry if implemented effectively. There is still work to be done, however, before this technology can become a practical reality. The greatest work is in working to reduce the effect of turbulent air in the boundary layer. This can be done through modifying fuselage design to allow for air to remain streamlined for longer, thus reducing the generation of vortices. Additionally, distortion-resistant turbofans need to be designed that can intake the boundary layer with a minimum of efficiency lost. These turbofans will need to be high-bypass, and intake as much of the boundary layer as possible to maximize the benefits that can be gained.

To develop these technologies, there needs to be a greater push for research into the technologies surrounding boundary layer ingesting propulsors. Airlines stand to gain a considerable amount from a reduction in fuel costs, and can help encourage research into new designs. The period of
being ready by 2035 is not a reason to push back research into this topic, but an encouragement that better aircraft technologies are within reach, if a greater emphasis is put on them.

SOURCES


ADDITIONAL SOURCES


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