A VTOL-UAV Inlet Flow Distortion Reduction Concept using a New Flow Control Approach: Double-Ducted-Fan (DDF)

Cengiz Camcı[1] and Ali Aktürk[2]*

ISROMAC 2016

International Symposium on Transport Phenomena and Dynamics of Rotating Machinery

Hawaii, Honolulu

April 10-15, 2016

Abstract

This paper briefly describes a novel ducted fan inlet flow-conditioning concept that will significantly improve the performance and controllability of ducted fans operating at high angle of attack. High angle of attack operation of ducted fans is very common in VTOL (vertical take-off and landing) UAV systems. The new concept that will significantly reduce the inlet lip separation related performance penalties in the edgewise/forward flight zone is named DOUBLE-DUCTED FAN (DDF). The current concept uses a secondary stationary duct system to control inlet lip separation related momentum deficit at the inlet of the fan rotor occurring at elevated edgewise flight velocities. The DDF is self-adjusting in a wide edgewise flight velocity range and its corrective aerodynamic effect becomes more pronounced with increasing flight velocity due to its inherent design properties. In this manuscript, after a comprehensive discussion of VTOL inlet flow distortion issues, a conventional baseline duct without any lip separation control feature is compared to two different double-ducted fans named DDF CASE-A and DDF CASE-B via 3D, viscous and turbulent flow computational analysis. Both hover and edgewise flight conditions are considered. Significant relative improvements from DDF CASE-A and DDF CASE-B are in the areas of vertical force (thrust) enhancement, nose-up pitching moment control and recovery of fan through-flow mass flow rate in a wide horizontal flight range.

Keywords

VTOL-UAV, ducted fans, , inlet flow distortion, double-ducted fan

[1] Prof. of Aerospace Engineering, Dept. of Aerospace Eng., Pennsylvania State University, USA
[2] currently, research Engineer at Siemens Energy, Orlando, Florida, USA

***Corresponding author**: cxc11@psu.edu

INTRODUCTION

Although there is a strong interest in V/STOL UAV community to effectively deal with the upstream lip separation problem of ducted fans, the inlet flow distortion problem is common to many present day fan rotors in a wide variety of applications. The current conceptual design study clearly shows that the DDF approach is applicable to any axial flow fan unit in which there is an inlet flow distortion mainly because the inlet flow direction is not well aligned with the axis of rotation of the axial fan system. A few other examples that will easily benefit from the DDF concept described in this document are the cooling fans that are horizontally mounted at the roof of electric/diesel train locomotive propulsion cabins, air conditioning fans frequently installed at the roofs of passenger buses and cooling/utility fans that are flush mounted to external surfaces in marine vehicles.

Current approach for proving concept validity: A conventional baseline duct without any lip separation control feature is compared to two different double ducted fans named DDF-A and DDF-B via 3D, viscous and turbulent flow analysis. Both hover and forward flight conditions are considered. Significant relative improvements from DDF-A and DDF-B are in the areas of vertical force (thrust) enhancement, nose-up pitching moment control and recovery of mass flow rate in a wide horizontal flight range. The results also show a major reduction of highly 3D and re-circulatory inlet lip separation zone when the DDF concept is implemented. The improved uniformity of fan exit flow and reduced differentials between the leading side and trailing side are obvious performance enhancing features of the novel concept. The local details of the flow near the entrance area of the leading side of the ducted fan are explained via detailed static pressure distributions and skin friction coefficients obtained from 3D viscous and turbulent flow analysis including a simulated rotor in the duct.

Upstream lip region flow physics for ducted fans in forward flight: Ducted fan systems horizontally moving at 90° angle of attack all inherently have an inlet flow direction that significantly deviates from the axis of the rotation. The inlet flow distortion near the leading side of all of these fan inlets becomes more problematic with increasing vehicle speed. The inlet flow distortion passing through a typical axial flow fan rotor becomes increasingly damaging with elevated forward flight velocity. The lip separation occurring on the inner side of the lip section severely limits the lift generation and controllability of V/STOL UAVs. In general, the leading side of the fan near the lip separation zone breathes poorly when compared to the trailing side of the ducted fan. The trailing side total pressure is usually much higher than the total pressure observed near the leading side at the exit of the rotor. The flow near the leading side is negatively influenced by a separated flow zone that is characterized as highly recirculatory, low momentum and turbulent.

Conventional ducted fan systems also have a tip clearance loss that is proportional with the effective tip gap inherent to each design. The specific shape of the tip platform and the surface properties and arrangement designed onto the casing surface also influences the magnitude of tip clearance loss. This aerodynamic deficiency is measured as a significant total pressure loss near the tip at the exit of the rotor all around the circumference when the vehicle is only hovering with no horizontal flight. When the vehicle transists into a horizontal flight zone, the total pressure loss/deficit at the exit of the rotor near the leading side is much more significant than “hover only” loss of the ducted fan. In addition to the conventional tip clearance energy loss, the rotor generates additional losses near the leading side, because of the re- circulatory low momentum fluid entering into the rotor near the tip section. This is clearly an off-design condition for an axial flow fan that is designed for a reasonably uniform inlet axial velocity profile in the spanwise direction. The immediate results of any inlet flow distortion entering into an axial fan rotor in horizontal flight are the loss of rotor’s energy addition capability to the fluid near the leading side, an imbalance of the local mass flow rates between the leading side and trailing side, an imbalance of the total pressure resulting at the rotor exit between the leading side and trailing side, a significant loss of lifting ability due to highly non-axisymmetric and unnecessarily 3D fan exit jet flow, unwanted nose-up pitching moment generation because the local static distributions imposed on the duct inner surfaces.

PAST STUDIES OF DUCTED FAN AERODYNAMICS IN FORWARD FLIGHT

Ducted fans that are popular choices in V/STOL uninhabited aerial vehicles (UAV) offer a higher static thrust/power ratio for a given diameter than open propellers They also provide an impact protection for the blades and improved personnel safety due to its enclosed fan structure as well as the lower noise level in the plane of the rotating fan blade. Figure 1 shows several currently popular ducted fan V/STOL UAVs as flight vehicles. The viscous flow characteristics of the ducted fan are complex. These vehicles need to be capable of flight in a broad range of atmospheric conditions, including the complex turbulent flow fields around buildings and trees. When a V/STOL ducted fan is in horizontal flight, because of the relative inlet flow dominantly parallel to its inlet plane, problems related to flow separation at the leading edge duct lip are encountered. The inlet flow separation leads to problems within the duct and may well result in a high nose-up pitching moment as the forward speed is increased. Therefore, measuring and predicting the mean flow characteristics of ducted fans is crucial to understand the problems related to reliable and controllable horizontal flights. Numerous studies have been undertaken in order to quantify the flow field characteristics around ducted fans. The operation of an axial flow fan with strong inlet flow distortion severely affects the performance of the rotor especially near the tip region of the blades.

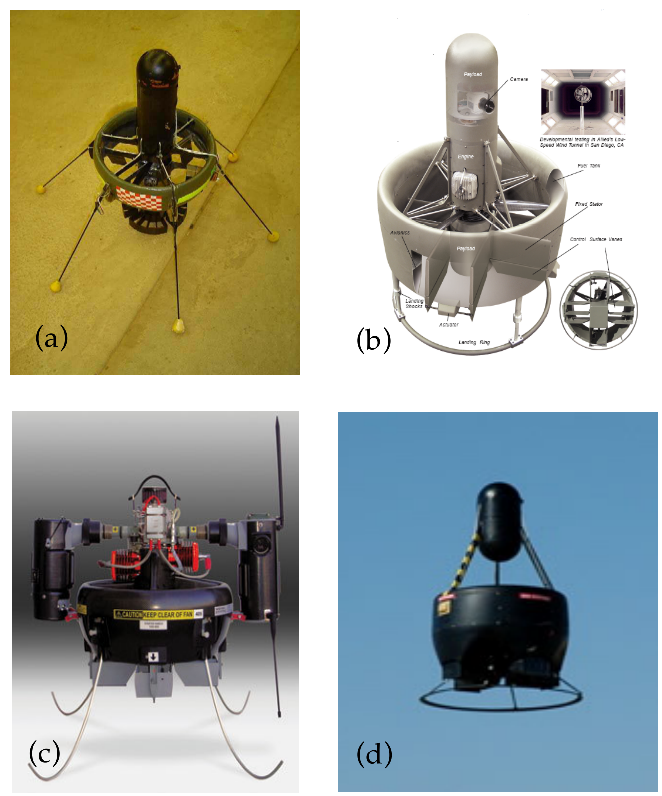


Figure 1. Examples of VSTOL/UAVs
(a) Mass Helispy (b) I-STAR (c) Honeywell MAV (d) BAE IAV2

Experimental aerodynamics studies in ducted fans: Experimental investigation has been the major approach to study the mean flow characteristics of the conventional ducted fan. [Abrego and Bulaga, 2002] performed wind tunnel tests to determine the performance characteristics of ducted fans for axial and forward flight conditions. Their study resulted in showing important effect of exit vane flap deflection and flap chord length on providing side force. [Martin and Tung, 2004] tested a ducted fan V/STOL UAV with a 10-inch diameter rotor. They measured aerodynamic loads on the vehicle for different angle of attacks in hover and different crosswind velocities. They also included hot-wire velocity surveys at inner and outer surface of the duct and across the downstream wake emphasizing the effect of tip gap on the thrust force produced. In addition, their study showed the effect of leading edge radius of the duct on the stall performance and stability of the vehicle. [Fleming, Jones and Lusardi, 2004] et al. conducted wind tunnel experiments and computational studies around a 12-inch diameter ducted fan. They concentrated on the performance of ducted fan V/STOL vehicles in crosswind.

Computational aerodynamics efforts in ducted fans: In addition to experimental studies, the ducted fan design and performance analysis were widely performed by using computational flow modeling. [Lind, Nathman and Gilchrist, 2006] carried out a computational study using a panel method. They compared their results to experimental results from [Martin and Tung, 2004]. Graf, Fleming and Ng, [2008] improved ducted fan forward flight performance with a recently designed leading edge geometry which was a significant factor in offsetting the effects of the adverse aerodynamic characteristics for elevated horizontal flight speeds. [He and Xin, 2006] developed the ducted fan models based on a non-uniform and unsteady ring vortex formulation. Numerical study in axial flight and horizontal flight condition was conducted and validated with measured data. [Chang and Rajagopalan, 2003] developed an accurate grid generation methodology known as “the curve adaptive option” to model several industrial ducted fans. An axisymmetric, incompressible Navier-Stokes solver was implemented to calculate the flow field of a duct fan. The computational results agreed well with available wind tunnel data. [Ahn and Lee, 2004] applied a computational method to their ducted fan system to identify the design parameters influencing its performance. Their ducted fan system was designed by using the stream-surface based axisymmetric analysis which considered overall physical characteristics and design parameters of the system. [Ko, Ohanian and

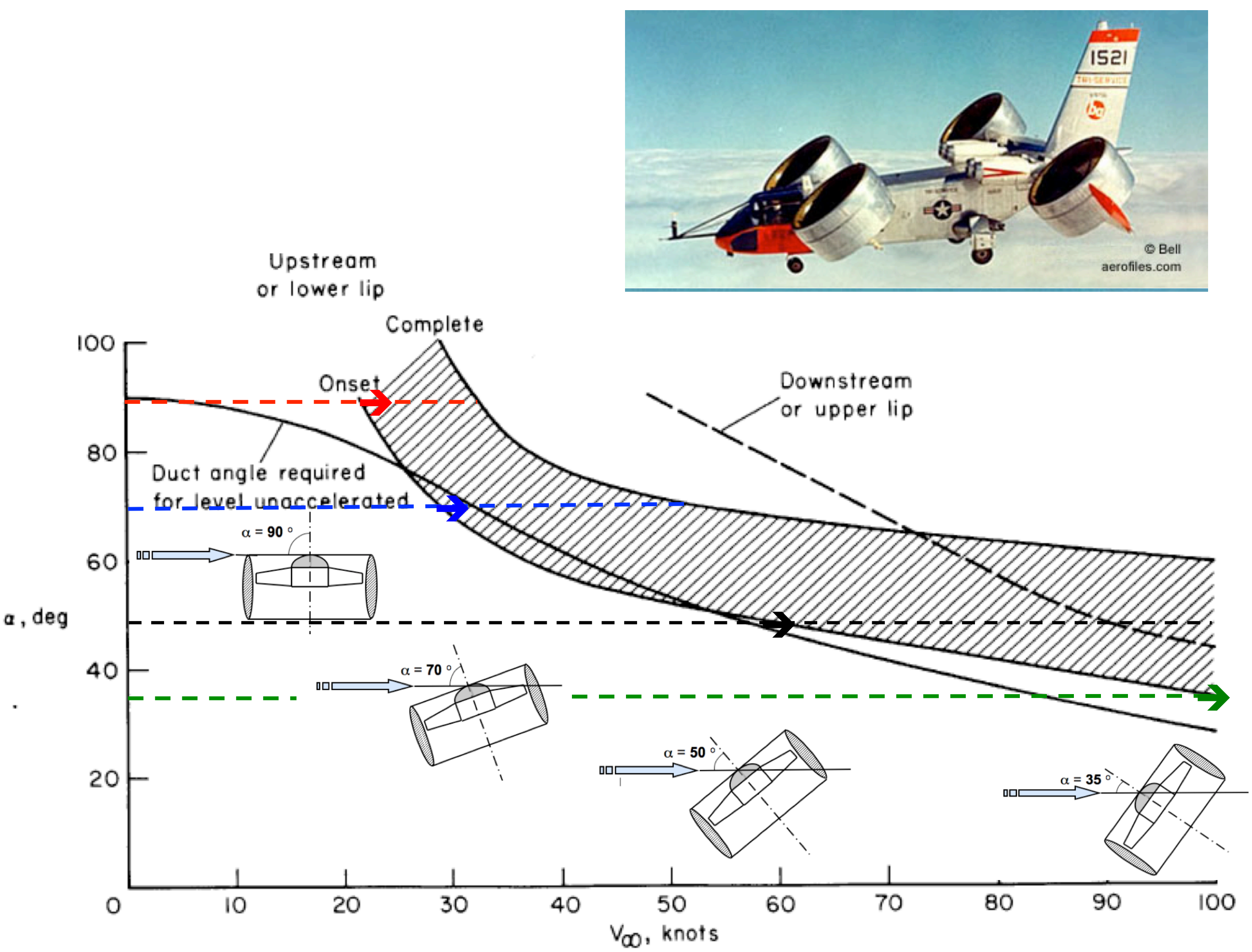


Figure 2. Upstream duct lip stall in function of angle of attack for X-22A ducted fan, [Mort and Gamse, 1967]

flight tests. Further, it was extensively used in the design of commercial ducted fans. Recently, [Zhao and Bill, 2008] proposed a CFD simulation to design and analyze an aerodynamic model of a ducted fan UAV in preliminary design phase with different speeds and angles of attacks. Although there are many ducted fan design and analysis related technical papers in the literature, the studies on the treatment of the problems of inlet lip separation of UAV systems are very limited.

Lip separation at high angle of attack: The new concept named "double-ducted Fan (DDF) is based on a very effective fluid mechanics scheme of reducing and controlling the upstream lip separation in a ducted fan operating at high angle of attack. Early research results clearly demonstrating the limits of onset of upstream lip separation in function of angle of attack are summarized in Figure 2. A full-scale duplicate of the V/STOL ducted propeller used on the Bell Aerosystems Co. X-22-A airplane was tested in Ames Research center by [Mort and Gamse, 1967]. Stall of both the upstream and downstream duct lips of this seven-foot diameter ducted fan was examined in function of angle of attack. The angle of attack of the ducted fan is measured between the approaching flow direction and the axis of rotation of the rotor. It was found that the onset of separation on the upstream lip would be encountered; however, complete separation on this lip would be encountered only during conditions of low power and high duct angle of attack corresponding to high rates of descent.

Tests of a wing-tip-mounted 4-foot-diameter ducted fan were performed for a limited range of operating conditions by [Mort and Yaggy, 1962]. At large duct angles of attack, the inside of the upstream duct lip stalled causing a rapid change in the duct pitching moments and accompanying increase in the power required. At low horizontal velocities this lip stall would probably limit the rate of descent of a vehicle with a wing tip mounted ducted fan. The wind tunnel test results shown in Figure 2 are highly relevant in demonstrating the beneficial aerodynamic characteristics of the double-ducted fan DDF concept presented in this paper.

Adverse effects of upstream lip separation in forward flight: At high angle of attacks, the onset separation at the upstream duct lip is accompanied by the formation of a separation bubble. Existence of a significant separation bubble severely distorts inlet flow of the fan rotor especially near the leading side and in the tip clearance region. Distorted inlet flow causes an asymmetric loading of the ducted fan which increases the power required for level un-accelerated flight and noise level. The immediate results of operating a ducted fan in horizontal flight regime especially at high angle of attack are as follows:

⇨ Increased aerodynamic losses and temporal instability of the fan rotor flow when "inlet flow distortion" from "the lip separation area" finds its way into the tip clearance gap leading to the loss of "energy addition capability" of the rotor.

⇨ Reduced thrust generation from the upstream side of the duct due to the rotor breathing low-momentum, re-circulatory, turbulent flow.

⇨ A severe imbalance of the duct inner static pressure field resulting from low momentum fluid entering into the rotor on the leading side and high momentum fluid unnecessarily energized near the trailing side of the rotor.

⇨ A measurable increase in power demand and fuel consumption when the lip separation occurs to keep up with a given operational task.

⇨ Lip separation and its interaction with the tip gap flow requires a much more complex vehicle control system because of the severe non-uniformity of the exit jet in circumferential direction and excessive nose-up pitching moment generation.

⇨ At low horizontal speeds a severe limitation in the rate of descent and vehicle controllability may occur because of more pronounced lip separation. Low power requirement of a typical descent results in a lower disk loading and more pronounced lip separation.

⇨ Excessive noise and vibration from the rotor working with a significant inlet flow distortion.

⇨ Very complex unsteady interactions of duct exit flow with control surfaces.

PREVIOUS PATENTS RELATED TO DUCTED FANS AND THEIR OPERATION IN FORWARD FLIGHT

Dorman, 2,951,661 (1960): Four ducted fan/propeller units located on each quadrant of a square vehicle footprint are used as lift generating components to be used in a heavier than air VTOL vehicle. The axis of rotation of each ducted fan unit is normal to the horizontal plane. This is one of the earliest presentations of using ducted fans in VTOL vehicle applications. This patent does not include any discussion lip separation problem in forward flight regime.

Bright, 2,968,453 (1961): Bright presented an early form of the two well known more recent vehicle concepts from Yoeli (Xhawk) and Piasecki (Piasecki Air Jeep). The two ducted fans are imbedded into a relatively flat fuselage with two fixed wings extending from the sides of the fuselage. An extensive adjustable shutter based exit flow control system was used to control the side force, yaw, pitch and roll motions of the vehicle. Inlet flow to the ducted fan unites were not treated using louvers, vanes or shutters of any kind. Leading side lip separation problem is not mentioned.

Fletcher, 2,988,301 (1961): A V/STOL aircraft concept using a counter-rotating ducted fan imbedded in a flat airfoil shaped fuselage was presented in an effort to transist a V/STOL aircraft to propel itself in high-speed flight. Forward flight related propulsive force was obtained from a conventional propeller mounted on the aft section of the vehicle. This vehicle has a provision to close the inlet surface of the fan rotor system completely in forward flight only relying on the lift force generated by the airfoil shaped fuselage and the propulsive force of the aft propeller. Inlet lip separation problem inherent to most ducted fan based systems of this type was never mentioned in this reference.

Piasecki, 3,184,183 (1965): This patent explains Frank Piasecki's well publicized "Air Jeep" concept that uses two counter-rotating lifting rotors in a tandem ducted-fan arrangement. This approach was unique because of a novel control linkage for its ducted vertical lift rotors for adjusting cyclic pitch and collective pitch of the rotating blades. The propulsive force in Piasecki's approach was obtained by cyclic and collective control of the rotor blades operating in a ducted fan arrangement. The rotor performance variation affected the local flow features near the leading side lip section of the duct. A significant component in this patent was the use of a movable spoiler in the inner part of the leading side lip of the duct. A movable spoiler that had a serrated edge is used to control local flow characteristics over the lip radius in an effort to reduce the drag (aerodynamic loss) generated over this area especially in horizontal flight. This is the first known attempt to the authors of this paper to correct the inlet lip separation problem using a movable spoiler located over an arc length of the inlet lip. However, the specific corrective action taken for the lip separation problem is based on adjustable inlet boundary layer tripping, using a deployable spoiler that is completely different from the working principles of the current double-ducted fan DDF concept.

Boyd, 3,159,224 (1970): This invention focused on a circular aircraft using an outer circumferential fan type ducted rotor mounted on air bearings. The ducted rotor was driven by outboard gas generators. This system used adjustable radial stator blades above the rotor. The stator blades were differentially adjustable in the forward and rearward quadrants to control the attitude of the aircraft with respect to its pitch axis. The stator blades in the left and right side quadrants could control the attitude of the aircraft with respect to its roll axis. The heading of the aircraft was controlled by means of a set of radial stator blades at the exit of the rotor. This approach only deals with the attitude control of a circular V/STOL vehicle and there is no treatment in this document in regard to possible inlet lip separation problem.

Wen 4,049,218 (1977): Wen described a VTOL aircraft using a centrifugal impeller generating a fan exit jet that can attain high exit jet velocities for effective vertical take-off. The centrifugal impeller output is passed through a diffuser section and deflected down to lift the aircraft. The impeller may be retracted down along its axis of rotation during transition to horizontal flight. The impeller exit is directed towards an exit nozzle at the aft section of the aircraft for the horizontal thrust needed for transition and forward flight. Although this is an interesting concept utilizing a centrifugal fan, its inlet flow characteristics and the influence of inlet flow distortion on the fan performance are not considered in this patent document.

Moller, 4,795,111 (1989): One of the earliest patents is a flying robotic platform using a conventional ducted fan and set of two mutually perpendicular vane systems from Moller. The patent focuses on flexible variable camber flaps and exit flow control features with no mention of inlet lip separation problem for this type of vehicle. Radio control of flexible control surfaces and unique arrangements of spoilers and flaps are described.

Cycon et al. 5,152,478 (1992): Sikorsky "Cypher" was an uninhabited aerial vehicle that included a toroidal fuselage and two co-axial counter-rotating rotors in a ducted fan arrangement. The two rotors provided both the vertical and horizontal thrust needed in hover and forward flight. A vertical take-off required a completely horizontal operation for obtaining a vertical downwash of the rotors to obtain the necessary lift for the aircraft. Transition to forward flight was achieved by tilting the fuselage in a 'Nose-down" mode to generate a horizontal thrust component. In the forward flight mode, the rotor inlet flow was usually altered such that the leading side lip had significant flow separation and the trailing side of the duct had incoming flow impinging on the inner side of the shroud creating a drag penalty. The inlet nose separation, impingement on the aft part of the shroud and the interaction of this inlet flow distortion with the rotors resulted in significant pitch-up moment generation on this vehicle. Cypher is one of the few VTOL vehicles that used cyclic pitch of the rotors in encountering the nose-up pitch pitching moment generation. Although this control feature unique to Cypher reduced the excessive pitching moment, it required considerable amount of power and did not eliminate the drag generation on the trailing side of the shroud.

Moffit et al. 5,150,857 (1992): Another solution in reducing the pitching moment was the use of an optimized toroidal fuselage airfoil profile. The cross sectional geometry of the toroidal airfoil was optimized such that the increasing pitching up moment with increased forward flight velocity was measurably reduced. The pitching up moment reduction was very effective after 20 knots vehicle speed up to 70 knots that was the maximum flight velocity tested. The lift of the shroud was also effectively increased via this toroidal fuselage airfoil optimization. While incorporation of an optimized toroidal airfoil was a viable option, to counteract nose-up pitching moments, there was a manufacturing penalty associated with the new profile and an adverse effect on higher speed flight characteristics.

Flemming et al. 5,419,513 (1995): Adding a highly cambered fixed wing to a toroidal fuselage was a significant method of dealing with excessive pitch-up moment generation encountered in forward flight of Sikorsky "Cypher". Flemming et al. used a high lift high camber airfoil with a center of lift located significantly aft of the quarter chord line of the airfoil. The symmetrically mounted fixed wings had centers of lift located aft ward of the fuselage axis of the toroidal fuselage in forward flight mode such that the fixed wings generate a nose-down pitching moment to counteract the nose-up pitching moment originating from the separated air flow over the leading side lip of the duct. The fixed wings were mounted in a fixed arrangement at a predetermined angle of incidence although a variable incidence system for the fixed wing is possible.

Swinson et al. 5,890,441 (1999): An autonomously controlled, gyroscopically stabilized, horizontal and vertical take-off and landing (HOVTOL) vehicle using to vertical lift devices was presented. Although this vehicle had similarities to most of the systems reviewed in this section, the specific patent focused on the autonomous controllability of the vehicle rather than the aerodynamic features and inlet lip separation problem.

Cycon et al. 6,170,778 (2001): A new method of reducing nose-up pitching moment during forward flight on a ducted uninhabited aerial vehicle was presented in [Cycon et al.,2001]. The vehicle consisted of a doughnut shaped fuselage that had a counter-rotating ducted fan with fixed wings attached to it for improved forward flight characteristics. The system also had a shrouded pusher propeller for horizontal thrust in forward flight. They. used the method of adding high lift cambered airfoils to the sides of the toroidal fuselage of Cypher to counteract the nose-up moments generated in forward flight. The specific fixed wings also had flaperons for the precise adjustments of lift forces needed at different horizontal flight regimes. This system also had directional turning vanes at the aft section of the pusher propeller to deflect propeller thrust downward, creating additional lift to counteract nose up moments in high-speed forward flight. They also noted that locating the pusher prop assembly aft of the duct reduced drag on the aircraft. The pusher prop has been found to draw turbulent air over the duct that would otherwise flow into the duct. This invention also suggested an excellent way of concealing the rotor system in high-speed flight. Conventional systems used relatively heavy and complex covers to block the air entrance to the ducted fan in high-speed forward flight. Operating the counter-rotating rotors at zero pitch resulted in a virtual cover system impeding the airflow into the duct. Drag was effectively reduced without the weight and complexity of rigid covers by blocking the flow and forcing it to flow over and under the aircraft,.

Cycon et al. 6,270,038 (2001): In addition to the flaperons in the fixed wings and the directional turning vanes in the propeller shroud exit, this invention reported one or more deflectors mounted to the bottom of the fuselage for further drag reduction. The deflectors effectively controlled airflow into the duct from the bottom of the fuselage during forward flight. These deflectors were passive and required no actuation. They opened and closed automatically based on the airflow through and over the duct. The combination of zero pitch counter-rotating rotors and passive flow deflectors on the bottom of the duct reduces the drag component on the aircraft between the open rotor and completely covered duct by about 80 %.

Moller, 6,450,445 (2002): A remotely controlled flying platform or a robotic platform was previously presented by Moller. This concept more recently presented by Moller used a counter rotating set of axial rotors in a ducted fan arrangement. Although an extensive set of fan exit flow control surfaces were used in this system, the inlet lip separation problem was not mentioned. The specific exit flow control surfaces are named “multiple adjustable air deflector assemblies” controlled by two servo-motors. The invention focuses on the actuation of the individual air deflectors via servo-mechanisms.

Yoeli, 6,464,166 (2002): This approach introduced by Yoeli uses a plurality of parallel spaced vanes located in front of and behind the ducted fan rotor of a VTOL vehicle. The vanes are selectively pivotal to produce a desired horizontal force component to the lift force applied to the vehicle. Many vane arrangements are presented for producing side force, roll, pitch and yaw movements of the vehicle. Symmetrical airfoil sections spaced at one chord length from each other are used. Each vane is split into two halves each half of all the vanes are being separately pivotal from the other half. This method does not deal with any aspects of upstream lip separation that will occur especially during horizontal flight of this VTOL vehicle.

Wagner 6,886,776 (2005): A VTOL personal aircraft (PAC) comprising of a fixed wing a fuselage and multiple of independently powered thrusters was explained by Wagner. The thrusters preferably integrated into the wing generated a flight system with a lift to drag ratio equal or greater than two. At least one thruster on each side of the fuselage preferably comprised a “levitator” to create additional lift from the airfoil like air inlet. Although multiple of ducted fan units were utilized on both sides of the fuselage, the inlet lip separation problem was not mentioned in the manuscript.

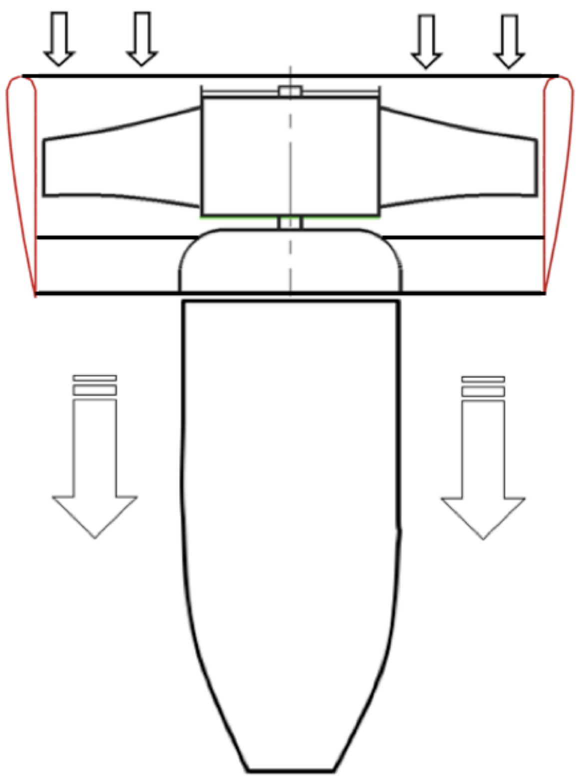
Yoeli, 6,883,748 (2005): This invention deals with the use of two ducted fans, four ducted fans and multiple free propellers on VTOL vehicle types already discussed by Yoeli in his previous patents. In addition to many military configurations possible with this vehicle, a hovercraft version using a flexible skirt extending below the fuselage is suggested.

Yoeli, 0,034,739 (2007): A ducted fan based VTOL vehicle including a fuselage having a longitudinal axis and a transverse axis, two counter-rotating ducted fan lift producing propellers are described by Yoeli. Many variations are described enabling the vehicle to be used not only as a VTOL vehicle, but also as a multi function utility vehicle. An unmanned version of the same vehicle is also described. Although an extensive use of inlet louvers and exit control surfaces are in place, there is no mention of an inlet lip separation control system near the leading side of the fans. The specific approach uses means for enabling the external flow penetrating the walls of the forward ducted fan for minimizing the momentum drag of the vehicle.

Yoeli, 7,275,712 (2007): This patent described an enhancement of his 2002 concept of parallel spaced vanes located in front of and behind the ducted fan rotor of a VTOL vehicle. Additional vane arrangements were presented for producing side force, roll, pitch and yaw movements of the vehicle. The left and right sides of the circular area at the rotor inlet and exit had parallel spaced vanes that were not in the direction of horizontal flight. The angle between the vanes and the flight direction was about 45 degrees for this specific patent. This patent did not have any description of inlet lip separation problem.

REFERENCE DUCTED FAN CHARACTERISTICS

Figure 3 shows the five bladed reference ducted fan that is used in the present DDF development effort at Penn State. The relatively poor forward flight characteristics of the reference ducted fan shown in Figure 3 are



Rotor hub diameter	52 mm
Rotor tip diameter	120
Duct inner diameter	126
Blade height h	34
Tip clearance t/h	8.7 %
Max. blade thickness @ tip	1.5
Tailcone diameter	52
Tailcone length	105

	HUB	***MID SPAN***	***TIP***
Blade inlet angle β_1	60°	40°	30°
Blade exit angle β_2	30°	45°	60°
Blade chord mm	32	30	28
Tip Mach number	$\Omega \cdot r_{tip} / \sqrt{\gamma R T_\infty}$		0.28
Reynolds number (mid-span)	$\rho W_m c / \mu$		$7\text{x}10^4$

Figure 3. Reference ducted fan characteristics

significantly improved via the new double-ducted fan (DDF) concept that is explained in the next few paragraphs. The geometric specifications of the reference ducted fan unit that is designed for small scale uninhabited aircraft are presented in Table 1. This unit is manufactured from carbon composite material and has six vanes at the exit of the fan in order to remove some of the swirl existing at the exit of the rotor. A tail cone is used to cover the motor surface and hide the electrical wiring. All computational 3D flow simulations of the reference duct including the rotor flow field are performed using the geometry defined in Figure 3 at 9000 rpm.

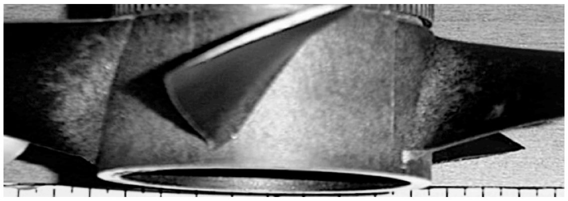


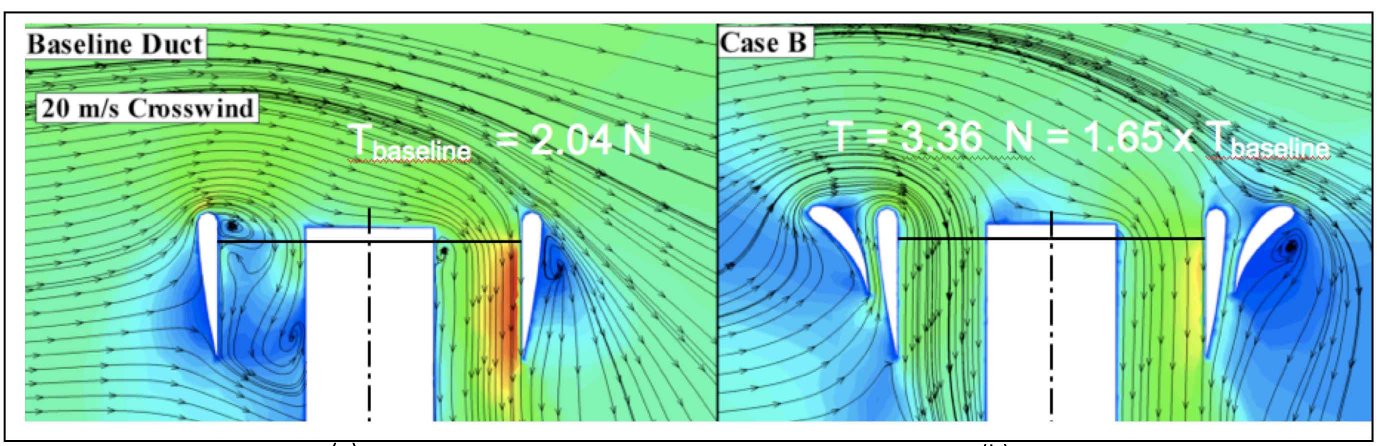
Figure 4. Reference ducted fan rotor (five bladed)

Although, the reference ducted fan rotor had a tip clearance of t/h=8.7 %, the tip clearance influence on the rotor downstream flow was knowingly excluded from the current 3D computational flow effort. The present simplified rotor flow model does not include tip clearance effects since the current effort is focused on the accurate simulation of the lip separation flow during forward flight of the vehicle.

DOUBLE-DUCTED FAN (DDF) AS A NOVEL CONCEPT

Operational character of the DDF: A novel ducted fan concept as a significant improvement over a standard ducted fan is explained in Figure 5. The poor forward flight characteristics of the reference duct as shown in Figure 5.a are effectively improved with the “Double-related to the forward lip separation increasingly occurring when the forward flight velocity is gradually Ducted Fan” concept as presented in Figure 5.b. A typical deficiency of a standard ducted fan is mainly increased as shown in the streamline patterns of Figure 5.a. The inlet flow near the leading side of the standard duct is highly separated, low-momentum and turbulent. The apparent flow imbalance between the leading side and trailing side of the standard ducted fan shown in Figure 5.a is also called an “inlet-flow-distortion”. Flow simulations in Figure 5.a show that the rotor barely breathes at the inlet section of the leading side although the trailing side passes a significant amount of flow. This flow imbalance amplified during the rotor “energy adding process” is one of the reasons of significant nose-up pitching moment generation. Figure 5.b also presents the Double-Ducted Fan (DDF) flow simulations indicating the effective inlet flow distortion reduction due to the unique aerodynamic properties of the (DDF) system. The upstream lip separation near the leading side is almost eliminated resulting in a more balanced rotor exit flow field between the leading side and the trailing side. More detailed descriptions of the local flow field improvements resulting from the novel Double-Ducted Fan (DDF) concept are discussed in the final part of this document. Although there may be many other potentially beneficial variations of the Double-Ducted Fan concept, only the specific (DDF) form defined in Figure 6.b will be explained in detail in the preceding paragraphs.

Geometrical definition of DDF: The DDF concept uses a second duct using a lip airfoil shape that has a much shorter axial chord length than that of the standard duct. The key parameter in obtaining an effective DDF arrangement is the size of the lip diameter D_L of the standard ducted fan. The second duct airfoil that is relatively cambered has a leading edge diameter set to $0.66D_L$ as explained in Figure 6.b. The angular



(a) (b)

Figure 5. Separated flow near the forward lip section of a standard ducted fan (left) and the flow improvements from the novel concept Double-ducted Fan (DDF) at 9000 rpm, colored by the magnitude of velocity (Red/high, Green/intermediate, Blue/low)

orientation and axial position of the second duct airfoil is extremely important in achieving a good level of flow shifted up in the vertical direction for proper inlet lip separation control. The vertical distance between the duct inlet plane touching the standard duct and the plane touching the second duct is about $0.33D_L$ as shown in Figure 6.b. The horizontal distance between the centers of the leading edge circles of the standard duct and outer duct is about $4D_L$. The axial chord of the second duct airfoil is about $5D_L$. The separation distance between the standard duct and second duct is controlled by the recommended throat width of $0.8D_L$ as shown in Figure 6.b. Figure 7 presents the actual dimensions of the double ducted fan CASE-B described in the present study. The leading edge diameter D_L=*8.5 mm (0.3 inch)*and the axial chord of the standard duct is *c= 58.6 mm (2.31 inch).* The general DDF design philosophy described in this section could easily be applied to obtain many other DDF geometries depending upon the vehicle size, rotor diameter, rotor disk loading and forward flight velocity range.

Converging-diverging channel in the duct: The second duct and the standard duct forms a converging-diverging channel starting from the trailing edge of the second (outer) duct that is located at about X=$5D_L$. The axial position of the throat section is about *0.45c* where *c* is the axial chord of the inner duct as shown in Fig. 6.b.

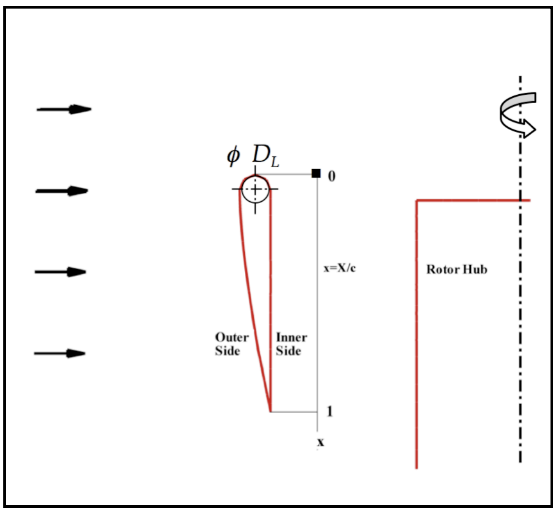


Figure 6.a Reference duct airfoil definition in a standard ducted fan arrangement

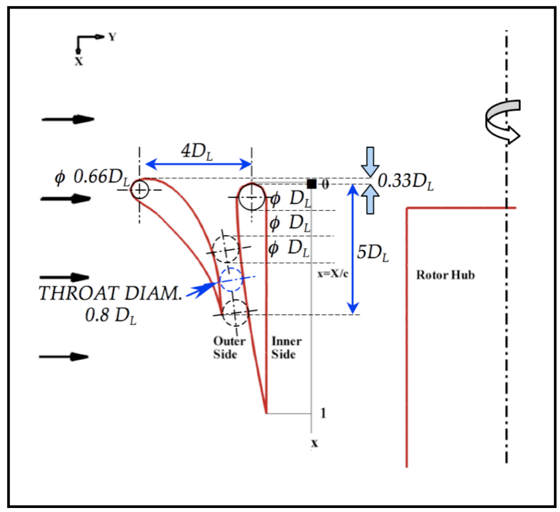


Figure 6.b Double Ducted Fan (DDF) geometry as a novel concept

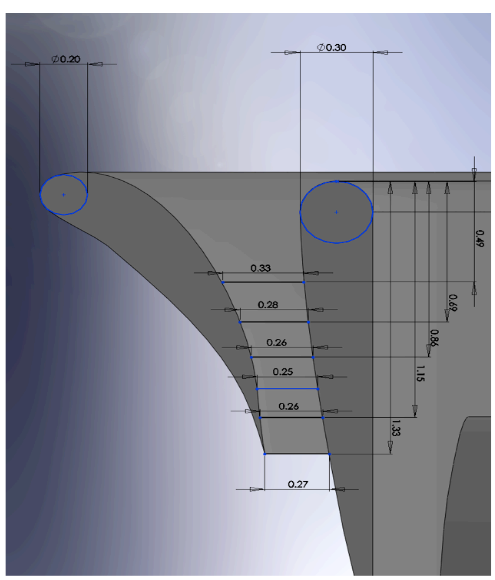
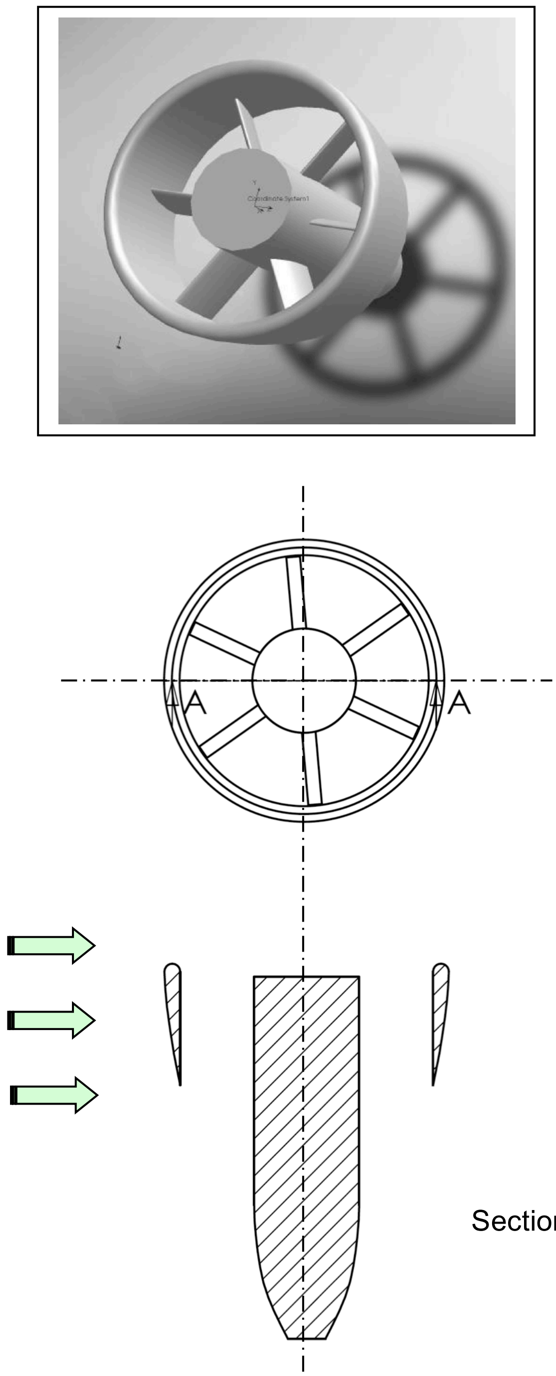
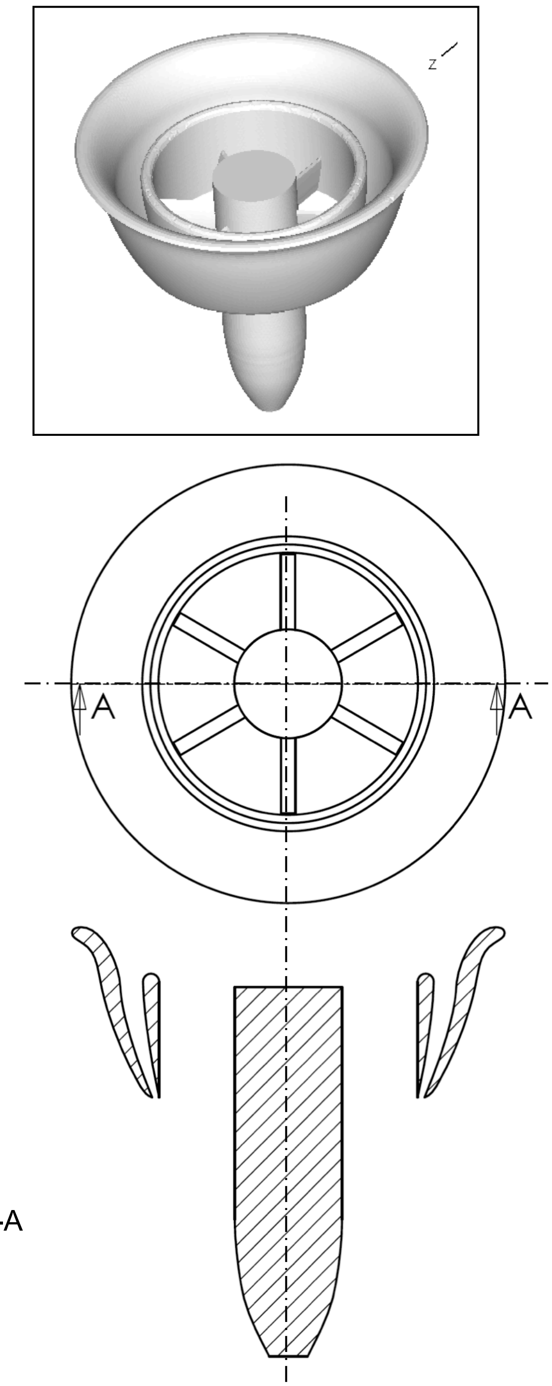


Figure 7. Actual dimensions of the Double Ducted Fan (in inches)

The duct width at the entrance of the converging-diverging duct is D_L. The entrance to the converging-diverging channel is at the trailing edge point of the second duct. There is a (vertically up) net flow in the converging-diverging duct of the DDF. This flow is due to increasing dynamic pressure at the entrance of the converging-diverging duct at $X=5D_L$ when the forward flight velocity is increased. The diverging part of the channel flow between the standard and outer duct is extremely important in this novel concept, since this decelerating flow is instrumental in adjusting the wall static pressure gradient just before the lip section of the





Section A-A

Figure 8. Baseline ducted fan
(Standard duct)

Figure 9. CASE-A
Tall Double Ducted Fan (DDF)

leading edge of the standard duct. The self-adjusting dynamic pressure of the inlet flow into the converging-diverging duct is directly proportional with the square of the forward flight velocity of the vehicle. The converging-diverging duct flow is in vertically up direction near the leading edge of the vehicle. The flow in the intermediate channel is vertically down when one moves away from the frontal section of the vehicle. This flow direction is caused by the relatively low stagnation pressure at the inlet of the intermediate channel at circumferential positions away from the leading edge. This vertically down flow induced by the static pressure field of the inner duct exit flow is likely to generate measurable additional thrust force for the DDF based vehicle.

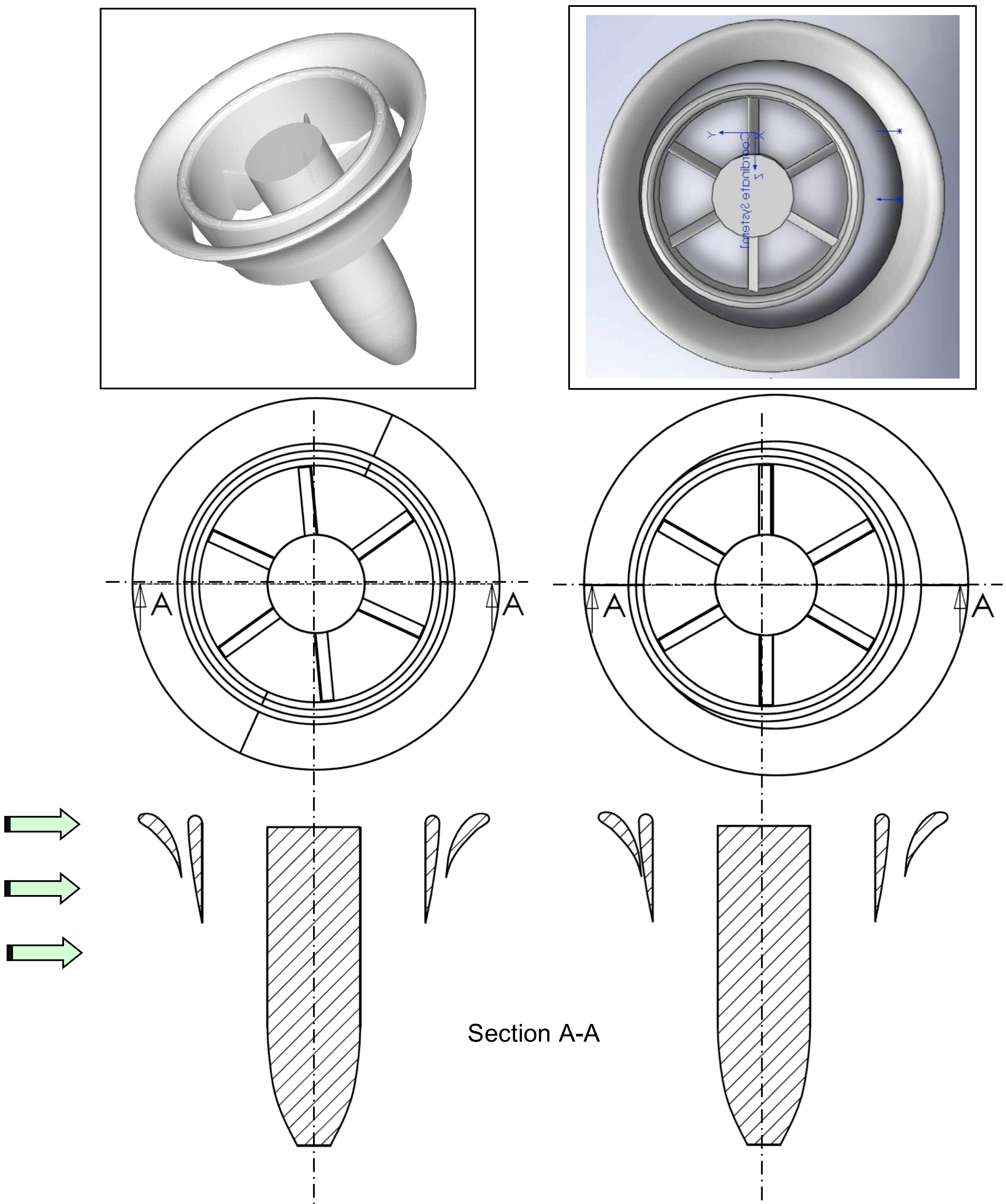


Figure 10. CASE-B
Short Double Ducted Fan (DDF)

Figure 11.
Eccentric Short Double Ducted Fan (DDF)

Various possible Double-Ducted Fan geometries: The standard duct and three possible variations of the Double-Ducted Fan (DDF) concept described in this study are presented in Figures 8 and 9,10,11. Three-dimensional solid models of the four duct configurations, a horizontal cross section and a vertical cross section are included in these figures**.**

CASE-A as shown in Figure 9 is termed as the Tall DDF. The Tall DDF is able to generate a significantly higher thrust in hover position than that of "only" the standard duct containing an identical rotor. However, in forward flight, due to the extended axial chord of the outer duct, the nose-up pitching moment generation is also significant in this duct design. This design has a throat section located at the trailing edge of the duct airfoils. Since the axial chord of the outer duct is longer than that of the inner duct this design may have a slight drag penalty when compared to the standard ducted fan.

Figure 10 shows the most effective Double-Ducted Fan (DDF) configuration **CASE-B** since it has the ability to generate a significant amount of thrust when compared to that of the "only' standard ducted fan configuration. Another important characteristic of CASE-B is its ability to operate without enhancing the nose-up pitching moment of the vehicle in forward flight. This configuration was analyzed in great detail mainly because of its combined ability to enhance thrust and reduce nose-up pitching moment in forward flight without a significant drag increase.

An **ECCENTRIC DOUBLE-DUCTED FAN** (DDF) concept is also shown in Figure 11. This concept requires a movable outer duct in order to control the throat area in the intermediate duct of the vehicle for a highly optimized forward flight performance. Variable throat mechanism introduced in this concept provides a greater range of operation in a DDF type vehicle offering a more accurate lip flow control over a much wider forward flight velocity range. Figure 11 shows a highly blocked second duct that is proper for very low forward flight velocity. It is required that the throat area is enlarged by moving the outer duct as the forward flight velocity is increased. Although an almost optimal lip separation control can be achieved with an eccentric (DDF), its mechanical complexity and weight penalty is obvious. The outer duct airfoil definition of this concept is the same as CASE-B that is described in detail in Figure 6.b.

SUMMARY AND CONCLUSIONS

This technical paper describes a novel ducted fan inlet flow conditioning concept that will significantly improve the performance and controllability of V/STOL "vertical/short take-off and landing" vehicles, UAVs "uninhabited aerial vehicles" and many other ducted fan based systems. The new (DDF) concept developed in this study deals with most of the significant technical problems in ducted fans operating at almost 90 ^{o} angle of attach, in the forward flight mode. The technical problems related to this mode of operation are as follows:

⇨ Increased aerodynamic losses and temporal instability of the fan rotor flow when "inlet flow distortion" from "the lip separation area" finds its way into the tip clearance gap leading to the loss of energy addition capability of the rotor.

⇨ Reduced thrust generation from the upstream side of the duct due to the rotor breathing low-momentum re-circulatory turbulent flow.

⇨ A severe imbalance of the duct inner static pressure field resulting from low momentum fluid entering into the rotor on the leading side and high momentum fluid unnecessarily energized on the trailing side of the rotor.

⇨ A measurable increase in power demand and fuel consumption when the lip separation occurs to keep up with a given operational task.

⇨ Lip separation and its interaction with the tip gap flow require a much more complex vehicle control system because of the severe non-uniformity of the exit jet in circumferential direction and excessive pitch-up moment generation.

⇨ At low horizontal speeds a severe limitation in the rate of descent and vehicle controllability may occur because of more pronounced lip separation. Low power requirement of a typical descent results in a lower disk loading and more pronounced lip separation.

⇨ Excessive noise and vibration from the rotor working with a significant inlet flow distortion.

⇨ Very complex unsteady interactions of duct exit flow with control surfaces.

The new concept that will significantly reduce the inlet lip separation related performance penalties in the forward flight zone is named "DOUBLE-DUCTED FAN" (DDF). The concept development uses a time efficient 3D computational viscous flow solution approach developed specifically for ducted fan flows. The present study summarizes only the most optimal approach after evaluating nine different double-ducted fan geometries for a wide range of forward flight velocities.

The current concept uses a secondary stationary duct system to control "inlet lip separation" related momentum deficit at the inlet of the fan rotor occurring at elevated forward flight velocities. The DDF is self-adjusting in a wide forward flight velocity regime. DDFs corrective aerodynamic influence becomes more pronounced with increasing flight velocity due to its inherent design properties.

The DDF can also be implemented as a "Variable Double-Ducted Fan" (VDDF) for a much more effective inlet lip separation control in a wide range of horizontal flight velocities in UAVs, air vehicles, trains, buses, marine vehicles and any axial flow fan system where there is significant lip separation distorting the inlet flow. Most axial flow fans are designed for an inlet flow with zero or minimal inlet flow distortion. The DDF concept is proven to be an effective way of dealing with inlet flow distortions occurring near the tip section of any axial flow fan rotor system operating at high angle of attack.

A partial coverage of the second duct near the leading edge section of the duct inlet is also an alternative way of obtaining a light-weight DDF implementation. A detailed assessment of DDF using a comprehensive computational fluid dynamics analysis is given in [Akturk & Camci, 2014]. A US Patent entitled "DOUBLE-DUCTED FAN" on the new concept described in this paper was obtained by the authors of this paper, [Camci & Akturk, 2014].

ACKNOWLEDGMENTS

The authors acknowledge the financial support provided by the PSU Vertical Lift Center of Excellence (VLRCOE) and the National Rotorcraft Technology Center (NRTC) (Under U.S. Army Research Office Grant No. W911W6-06-2-0008). They wish to thank Dr. Ozhan Turgut for his support throughout this effort. Cengiz Camci also acknowledges the support generously provided to him by TUBITAK, The Scientific and Technological Research Council of Turkey and Istanbul Technical University, during his sabbatical leave in 2015. Mr. R.Auhl, M. Catalano and K. Hellen of Aerospace Engineering at Penn State provided significant technical expertise in all of our ducted fan related experimental and large scale computing efforts.

REFERENCES

Abrego, A., I. and Bulaga, R., W., "Performance Study of a Ducted Fan System", *AHS Aerodynamics, Aeroacoustic , Test and Evaluation Technical Specialist Meeting*, San Francisco, CA, Jan 2002.

Ahn, J., Lee, K.T.,"Performance Prediction and Design of a Ducted Fan System" *40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, Fort Lauderdale, Florida, July 2004.

Akturk, A. and Camci, C.," Lip Separation and Inlet Flow Distortion Control in Ducted Fans Used in VTOL Systems," ASME paper GT2014-26249, ASME Turbo Expo 2014, June 2014.

Bright, C.E., "Ducted Fan Aircraft", US Patent No: 2968453.

Boyd et al. ,"Vertical Takeoff And Landing Aircraft", US Patent No:3519224.

Camci, C. and Akturk, A., "Double-Ducted Fan" US Patent No: US8,821,123 B2, September 2014.

Chang, I.C., and Rajagopalan, R.G., "CFD Analysis for Ducted Fans with Validation" *21th AIAA Applied Aerodynamics Conference*, Orlando, Florida, June 2003.

Cycon, J.P. et al., "Method Of Reducing A Nose-Up Pitching Moment On A Ducted Unmanned Aerial Vehicle", US Patent No:6170778.

Cycon, J.P., et al., "Unmanned Aerial Vehicle With ounter-Rotating Ducted Rotors And Shrouded Pusher-Prop", US Patent No:6270038.

Cycon, J.P., Rosen,K.M., Whyte, A.C., "An Unmanned Flight Vehicle Wherein two Counter-Rotating Rotors are Positioned within a Toroidal Fuselage and in which Rotor Pitch Solely is Utilized to Generate all Required Lift, Pitch, Roll, Yaw And Vibration and Stress Control for the Vehicle" US Patent No: 5152478.

Dorman et al. "Aircraft Having A Plurality Of Annular Wings", US Patent No:2951661.

Fleming J., Jones. T., Lusardi, J., Gelhausen P., Enns D., "Improved Control of Ducted Fan VTOL UAVs in Crosswind Turbulence" *AHS 4th Specialist's Conference on Aeromechanics*, San Francisco, CA, Jan 21-23, 2004.

Flemming, R.J., Rosen, K.M., Sheehy, T.W., "Ancillary Aerodynamic Structures For An Unmanned Aerial Vehicle Having Ducted, Coaxial Counter-Rotating Rotors", US Patent No: 5149513.

Fletcher, C.I., "Ducted Fan Aircraft", US Patent No: 2988301.

Graf, W., Fleming, J., Wing, Ng., "Improving Ducted Fan UAV Aerodynamics in Forward Flight" *46th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, Jan 2008.

He, C. and Xin, H., "An Unsteady Ducted Fan Model for Rotorcraft Flight Simulation" *62th AHS Forum*, Phoenix, Arizona, May 2006.

Ko, A., Ohanian, O.J., Gelhausen, P., "Ducted Fan UAV Modeling and Simulation in Preliminary Design" *AIAA Modeling and Simulation Technologies Conference and Exhibit*, Hilton Head, South Carolina, August 2007.

Lind, R., Nathman, J. and Gilchrist , I., "Ducted Rotor Performance Calculations and Comparisons with

Experimental Data" *44th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, Jan 2006.

Martin, P. and Tung, C., "Performance and Flowfield Measurements on a 10-inch Ducted Rotor VTOL UAV", *60th Annual Forum of the American Helicopter Society,* Baltimore, MD, June 7-10, 2004.

Moffit, R.C., Owen, S.J., "Shroud Geometry For Unmanned Aerial Vehicles", US Patent No: 5150857.

Moller, P.S., "Stabilizing Control Apparatus For Robotic Or Remotely Controlled Flying Platform" US Patent No:6450445.

Moller, P.S., "Robotic Or Remotely Controlled Flying Platform" US Patent No: 4795111.

Mort, K.W. and Gamse, B., "A Wind Tunnel Investigation of a 7-foot Diameter Ducted Propeller," *NASA Technical Note, NASA TN D-4142*, 1967.

Piasecki, F.N., "Flying Platform", US Patent No: 3184183.

Swinson, J. et al., "Horizontal And Vertical Take-Off and Landing Unmanned Aerial Vehicle", US Patent No:5890441.

Wagner, J. et al., "VTOL Personal Aircraft", US Patent No:6886776.

Wen, L. , "Vertical Take-Off And Landing Aircraft", US Patent No:4049218.

Yoeli, R., "Ducted Fan Vehicles Particularly Useful as Vtol Aircraft", US Patent No:6464166.

Yoeli, R., "Vehicles Particularly Useful As VTOL Vehicles", US Patent No:6883748.

Yoeli, R., "DUCTED FAN VTOL VEHICLES", US Patent No:2007/0034739.

Yoeli, R., "Ducted Fan Vehicles Particularly Useful As VTOL Aircraft", US Patent No:7275712.

Zhao, H.W. and Bil, C., "Aerodynamic Design and Analysis of a VTOL Ducted-Fan UAV" *26th AIAA Applied Aerodynamics Conference*, Honolulu, Hawaii, August 2008.