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ON THE USE OF AN INFLATABLE RUBBER LIP TO IMPROVE THE REVERSE THRUST FLOW FIELD IN A VARIABLE PITCH FAN

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ABSTRACT

The installed Variable Pitch Fan (VPF) reverse thrust flow field is obtained from the flow solution of an integrated airframe-engine research model for the complete reverser engagement regime during the aircraft landing run from 140 knots to 40 knots. The model includes a twin-engine airframe, complete flow path representation of a future 40000 lbf high bypass ratio geared turbofan engine, and a bespoke reverse flow-capable VPF design. The reverse thrust flow field, at all speeds, indicates that the reverse flow out of the nacelle inlet is washed downstream by the freestream towards the engine exit regions. Consequently, reverse flow enters the engine through the bypass nozzle from a 180° turn of the washed-down stream. This results in a region of circumferentially varying separated flow at the nozzle lip that acts as a blockage to the reverse flow entry into the engine.

To mitigate the blockage issue, a smooth guidance of the reverse flow into the engine to avoid separation can be achieved by using an inflatable rubber lip that would define a bell-mouth like geometric feature with a round radius at the nacelle exit region. In nominal engine operation, the rubber lip would be stowed flush within the contours of the optimized nacelle surface. The design space of the rubber lip is studied by considering different rounding radii and locations of the turn radius with respect to the nacelle trailing edge. The choices of the design parameters are chosen by considering the nacelle edge thickness, inflation air volume requirement, weight, and thickness of support structures. The effect of these designs on the reverse thrust flow field is studied by incorporating the designs into the integrated model, with realistic installation related restrictions. It is observed that a rounding radius of 0.1x nacelle length is sufficient to reduce the blockage and increase the ingested reverse flow by 47% to 18% in the 140 to 40 knots landing speed range. The

inflatable rubber lip represents a design modification that can aid in the improvement of VPF reverse thrust operation, in cases where an augmentation of reverse thrust capability over the baseline is desired.

Keywords: Variable Pitch Fan, blockage, reverse thrust, rubber lip, separation mitigation, installed flow field.

INTRODUCTION

Future efficient civil turbofan engine architectures have been envisaged with high bypass ratios in the range 12 – 14 to maximize the benefits obtained from high propulsive efficiencies. Such large high bypass ratio engines would require a low-pressure ratio fan from thermodynamic performance considerations to achieve high overall engine efficiency. In such cases, as noted from several engine and aircraft performance studies, the VPF is a better alternative from weight, performance, and mechanical design considerations than a variable area nozzle to manage the off-design operational issues of the low pressure ratio fan and to optimize its operation [1-4]. Moreover, the large size of future high bypass ratio engines results in the conventional cascade-based nacelle mounted thrust reverser to be proportionally heavy and eat up a significant portion of the aircraft-engine weight budget. Therefore, further aircraft mission fuel burn benefits can be obtained if the VPF is used to generate reverse thrust and this would pave the way for development of low installation drag, low weight, ‘slimline’ nacelles. The advantages provided by the reverse thrust capable VPF in addressing the higher weight and installation drag penalties associated with large high bypass ratio engines makes the VPF an important technology enabler for successful development of efficient engines.

The VPF is used to reverse the airflow by shifting the cascade capture throat area to the fan aerofoil trailing edge side. This can be achieved by rotating the fan blade aerofoils by 90°, typically through ‘feather pitch’ setting because of lower restrictions on the fan nominal design. The airflow reversal using VPF was explored by NASA in the Quiet Clean Short-haul Experimental Engine and the Advanced Ducted Propulsor (ADP) programs. In both these programs, reverse flow capable VPF turbomachinery designs were developed. The behavior of these designs was explored, and reverse flow characteristics were studied in scaled down rig setups in an uninstalled isolated engine flow path. Subsequently, the reverse flow fan aerodynamic behavior in the scaled static isolated rig was described in a recent computational study. Beside these scaled rig studies, a VPF design in an engine was also tested in an outdoor static rig. The engines in these outdoor tests were designed with flared outlet nozzle petals, called ‘exlets’, to aid the ingestion of reverse flow into the engine [5-10].

However, all these previous studies focused on developing the reverse flow turbomachinery design using isolated rig tests. The limited outdoor engine tests were also done only in static conditions. No studies were carried out to understand how a reverse flow capable VPF design in an engine would operate in installed dynamic conditions during the aircraft landing run. To address this research gap, the authors studied a reverse flow VPF design in a representative future high bypass ratio engine and described several aspects of

the realistic dynamic installed reverse thrust behavior using flow solutions obtained from an integrated airframe-engine research model [11-13]. The installed reverse thrust behavior was obtained by considering the VPF operating in a baseline representative unmodified aircraft-engine configuration without any flared nozzle 'exlets' as in the outdoor engine tests.

The observations from the installed reverse thrust flow field indicated that it would be desirable to have a design modification that could aid in increasing the amount of reverse flow ingested into the engine. But for such a design modification, the 'exlets' used in the previous tests are not a viable option because: 1. the flared exlets would require complicated actuation mechanisms which can end up being proportionally heavy when applied to large diameter bypass nozzles in future high bypass ratio engines. 2. The flared exlets are essentially variable area nozzles, which if used along with the VPF would lead to an overall non-optimal system design, because two variable systems, both of which could be independently used to manage fan operability are sub-optimally utilized. These penalties can potentially derail the benefits obtained from the VPF. 3. The exlets were considered as a design modification which will work in static conditions. In addition to the exlets, few other patented design modifications that would penalize the nominal flight profile engine operation, such as serrated nacelle trailing edges, combination of exlets with additional openings and radial blades upstream of the VPF have been conceived to work based on only the static conditions [14-16]. However, to make the VPF reverse thrust system feasible, any proposed design modification should work in the aircraft installed dynamic conditions faced during the aircraft landing run.

Therefore, in this work an inflatable rubber lip, which can act as an aid to increase the reverse flow into the engine in the installed dynamic conditions without penalizing the nominal flight performance is presented. The design concept is developed from the flow field observations obtained from the 3D RANS solutions of the baseline unmodified aircraft-engine research model with the VPF in reverse thrust operation, which indicates a blockage in the bypass nozzle exit, as explained in detail in the paper. The inflatable rubber lip is designed to provide a smooth guidance of the reverse flow from the engine external regions to remove the blockage at the bypass nozzle exit (A look at Figures 2 and 3 can provide an appreciation of the reverse thrust flow field and the improvement targeted by the rubber lip design). The baseline aircraft-engine research model is modified to include the inflatable rubber lip geometry near the engine exit to understand the effect of the rubber lip in improving the reverse thrust flow field in the installed actual operating conditions. The design parameters which will aid in the design of such an inflatable rubber lip, in terms of its geometric dimensions, as installed in a representative aircraft implementation, and the change in the reverse thrust flow field are discussed in the paper.

BASELINE RESEARCH MODEL

Model Description

An integrated airframe-engine-VPF research model that features a reverse flow capable VPF design in a future high bypass ratio geared turbofan engine and installed onto an appropriate twin engine airframe is developed to explore the installed VPF reverse thrust

flow field during the aircraft landing run [13]. In order to appropriately resolve the VPF reverse thrust flow field in realistic conditions, a translating ground plane to mimic the rolling runway during the landing run is defined as the base of a large cuboidal far field domain within which a symmetric half of the airframe-engine model with the VPF in reverse thrust is placed, as shown in Figure 1. The key features of the baseline research model are:

1. VPF: The reverse flow capable VPF design used in the model is developed from the NASA ADP rig design, which was experimentally validated for reverse flow behavior. The 22-inch rig design is scaled to the 110-inch diameter of the engine in the present model, and the rig hub-to-tip ratio of 0.42 is modified to 0.3, so as to be representative of the high efficiency fan designs used in high bypass ratio engines. The blade profile definitions and stacking lines are appropriately scaled to the engine dimensions with the same spanwise stage loading and flow coefficient distributions. In the forward flow mode, the design has a pressure ratio of 1.27 (as defined from the engine performance cycle), temperature ratio of 1.08 and a tip speed of 245 m/s. The behavior of this design in reverse flow is characterized by a computational study in which the VPF is modelled to operate in a duct. The reverse flow characterization study indicated that when the aerofoil profiles are rotated through feather-pitch by, $\zeta 1^\circ$ and $\zeta 2^\circ = \zeta 1^\circ - 6^\circ$ (both values near 90°), the design can generate reverse stream mass flow up to 0.55x of the forward flow with an operating pressure ratio in the range of 1.1 to 1.2 within a rotational speed range that is within $\pm 15\%$ of the fan forward flow rotational speed. Based on the observations from the reverse flow characteristics, the VPF in a representative reverse flow stagger angle setting of $\zeta 1^\circ$, is placed in the integrated model for this design exploration study.

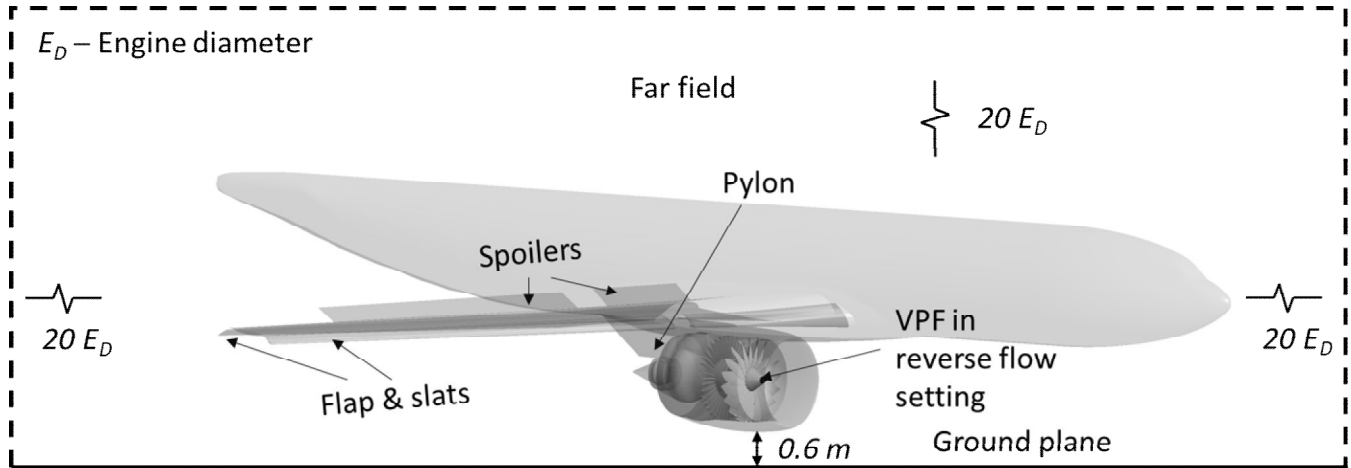


FIGURE 1: INTEGRATED AIRFRAME-ENGINE-VPF RESEARCH MODEL – BASELINE CONFIGURATION [13]

2. Engine: The engine is a geared two-spool architecture with 14 bypass ratio at design point and 40000 lbf of maximum take-off thrust. In addition to the VPF in reverse thrust mode, the engine model includes a full 360° representation of the complete bypass nozzle flow path including the splitter into the core engine, outlet guide vanes and the pylon bifurcation strut. Parts of the core engine such as

the entry duct, core exhaust duct, core nozzle and aft-body plug are also included to capture the effect of hot stream flow on reverse flow development. The design of the flow path and the blade rows is done using in-house tools and is representative of conventional modern turbofan engine practice.

3. Airframe: An in-house developed bespoke nacelle and pylon design is used to install the engine to a typical 300 passenger twin engine airframe that uses 40000 lbf turbofan engines. The airframe is a scaled version of an airframe used for validation of high-lift flows. The airframe control surfaces are in landing configuration with the flaps, slats, and spoilers appropriately deployed. The engine is placed with a typical ground clearance of 0.6 m from the rolling runway which defines the base of the far field domain that extends at least 20 engine diameters along the three axes from the engine's centerline.

The components of the baseline integrated model do not feature any additional modifications to aid the operation of the reverse thrust VPF. This is done to ensure that the reverse thrust flow field in a baseline configuration acts as a baseline for further design refinement studies. Each of the constituent components of the integrated research model are validated with the known forward flow behavior benchmark: the VPF with NASA ADP characteristics, the engine flowpath with a generic layout of a similar thrust class geared turbofan and the airframe with the coefficient of pressure distributions. Moreover, the integrated model is made modular to aid quick design changes to specific parts of the model without affecting the rest of the model and study the effect of such design changes on the reverse thrust flow field.

Flow Field Solution Methods

A hybrid discretization strategy with an unstructured grid topology for the airframe and bypass nozzle domains, where the flow direction is not known a priori, and a structured grid topology for the turbomachinery and duct components, where the geometric boundaries aid the definition of aligned grid elements, is adopted in this study. An extensive Grid Convergence Index (GCI) study using the Richardson' Extrapolation method, in which the GCI value does not exceed 0.006, for both local flow variables like fluxes, fan characteristic parameters and for global reverse thrust parameters of interest is used to finalize a grid size of ~73 million elements [17]. Both the unstructured and structured grid elements are verified to ensure that low quality, high aspect ratio, skewed, negative volume elements are not present in the computational domain.

A well-defined numerical problem to resolve the baseline 3D RANS reverse thrust flow field is defined by specifying the freestream velocity in the far field domain and the ground plane translational velocity that is the same as the aircraft speed for the complete landing run. The baseline configuration reverse thrust flow field is generated for the VPF at the ζ_1° reverse flow stagger angle setting and the rotational speed at engine landing operating point. Additionally, the boundary condition to mimic the core engine is specified in terms of axial velocity and total temperature distributions obtained from the engine performance data for the landing condition to sustain the

VPF rotational speed. Appropriate fluid-fluid general grid interfaces between stationary fluid domains and frame change grid interface models between the rotational and stationary domains in the computational model are specified. The flow solution of the RANS equations is obtained using the finite volume, conservative, fully implicit, second order accurate solution algorithm in ANSYS-CFX with the turbulence closure specified by the two-equation $k-\omega$ Shear Stress Transport (SST) model [18]. All the near-wall elements in the computational model have a $y^+ < 1$ to enable an explicit resolution of near-wall flow physics. Adaptive flow traverse time-based zonal timescale factors are used to achieve the desired numerical convergence behavior in the integrated model that has widely different flow physical timescales in the model sub-domains. Solver residual monitoring tolerance and statistical evolution of parameters of interest over a fixed iteration interval is considered to determine the convergence and obtain the reverse thrust flow field vector solution space for the complete aircraft landing run. The detailed description of the model development, computational discretization methods, flow solution methodology and the rationale for utilization of the complex integrated model are discussed in the model development and installed fan flow field description work published by the authors [11, 13].

Reverse Thrust Flow Field

The general reverse thrust flow field when the VPF is engaged in reverse thrust mode during the aircraft landing run is shown in Figure 2. In this mode, the reverse flow emanates from the fan aerofoil passages towards the nacelle inlet. The momentum of the freestream air causes it to penetrate the nacelle inlet regions where it meets the reverse flow from the fan and thereafter it is entrained to join the reverse flow. When the entrained stream and the reverse flow reach the nacelle inlet lip, they are washed downstream towards the engine exit regions by the freestream flow around the engine. Near the engine exit regions, the washed-down flow turns 180° to enter the engine through the bypass nozzle exit. The development of the VPF reverse flow streamlines are shown by red arrows in the Figure 2.

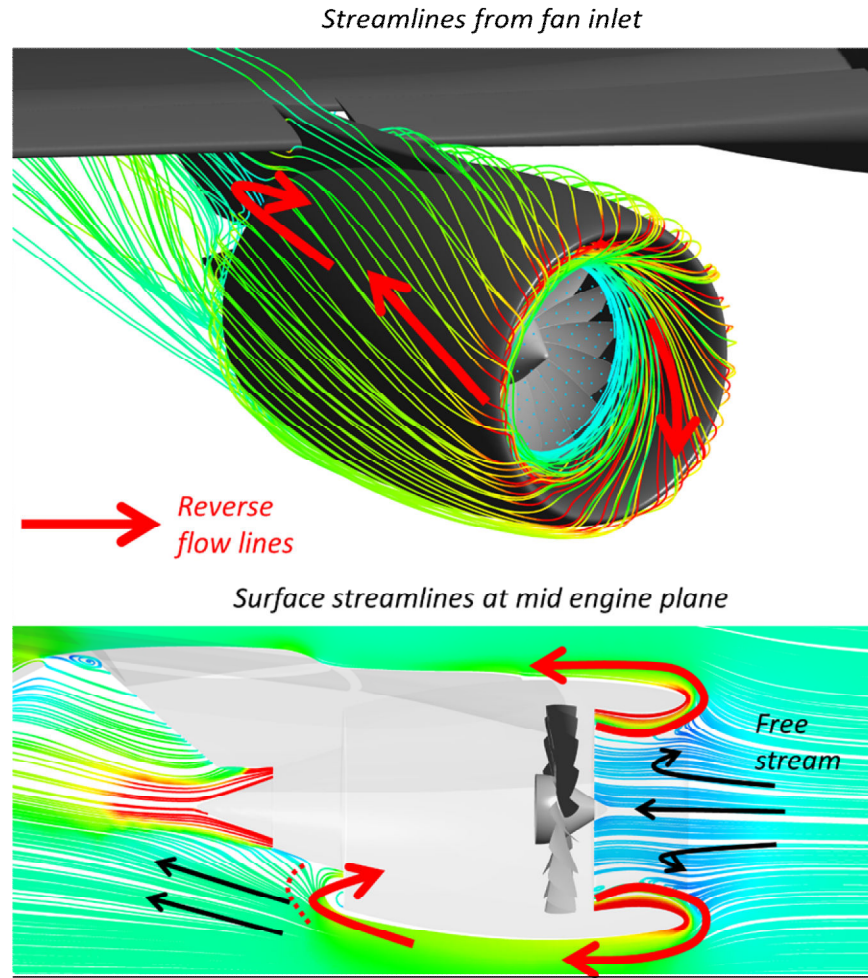


FIGURE 2: BASELINE INSTALLED REVERSE THRUST FLOWFIELD FEATURES [12]

The features of the general reverse thrust flow field remain similar from the aircraft touch down velocity of 140 knots to a thrust reverser shut-down velocity of 40 knots, except for minor differences in the outward extent to which the reverse stream spreads into the regions around the engine because of the reduction in the freestream momentum with landing speed. This leads to a situation in which, throughout the aircraft landing run, the reverse flow into the engine develops from a sharp 180° turn of washed-down flow from the engine exit regions. Consequently, when the flow turns 180° at the bypass nozzle exit, there is a region of separated flow in the outer annular regions of bypass nozzle exit plane throughout the reverser engagement regime. The axial velocity contours, which indicate this outer annular separated flow region, at the bypass nozzle exit for different landing speeds is shown in Figure 3. The axial velocity contours indicate that the reverse flow (red-yellow regions in the figure) stream tube occupies only the inner third of the annulus at the touch down velocity of 140 knots and the stream-tube gradually stretches up to the outer third of the annulus at 40 knots. The reverse flow stream tube stretches as the aircraft landing speed reduces because the lower freestream velocity results in a reduction in the flow

ingress velocity of the 180° turn. Moreover, the extent of the separated zone and the stream tube exhibits a circumferential variation highlighted by two major features: 1. An increase in the ingested reverse flow at the wing inboard side (right side of the plane). This is because the washed-down reverse flow impinges on the pylon at an angle, as shown in Figure 2, and causes a region of separated flow in the wing inboard side of the pylon. Consequently, the VPF suction acts on slow moving fluid on the wing inboard side and results in a larger amount of reverse flow. 2. A reduction in the amount of reverse stream near the ground (lower-right side of the plane because of the washed-down flow angle). The ground effect induced acceleration of the washed-down reverse flow escapes the VPF suction and results in this near ground reduction of the ingested reverse flow.

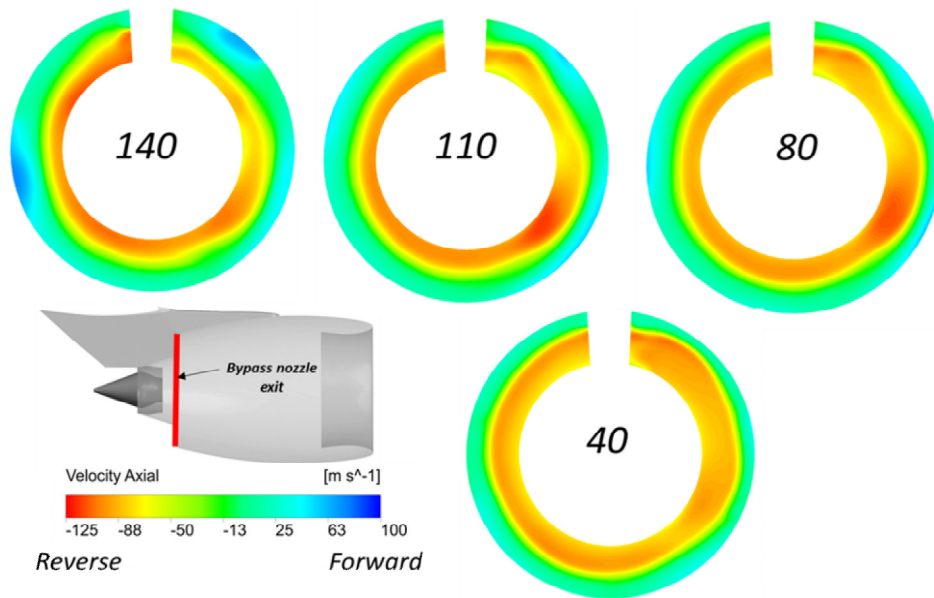


FIGURE 3: FLOW CONTOURS AT BYPASS NOZZLE EXIT – VIEW FROM ENGINE FRONT

The presence of the circumferentially varying outer annular separation region throughout the VPF thrust reverser engagement regime is undesirable because it acts like a blockage and reduces the effective area from which the reverse flow enters the engine. Therefore, it is desirable to conceive a design modification that could reduce this blockage and aid in the ingestion of more reverse flow into the engine. The flared outlet nozzle ‘exlets’ which were conceived as an enhanced flow capture mechanism for static conditions would not be effective during the active aircraft landing run. This is because in the static conditions, the reverse flow develops from regions behind the engine exit without a 180° turn as in the installed dynamic conditions. Moreover, as explained in the introduction, the implementation of ‘exlets’ would lead to a sub-optimal system design and introduce significant weight penalties because of the large diameter cold nozzles in high bypass ratio future engines. Alternatively, an inflatable rubber lip is discussed as a possible design improvement to reduce the separation in the next section.

RESEARCH MODEL WITH INFLATABLE RUBBER LIP

Design Development

The smooth guidance of the 180° reverse flow ingress turn into the engine to avoid separation at the bypass nozzle lip can be achieved by using an inflatable rubber lip in the nacelle outer surface near the bypass nozzle exit region. During the nominal forward flow operation, the rubber lip is not inflated and is stowed along the contours of the optimized nacelle surface design. When the aircraft is in the landing run, the rubber lip is inflated to define a bell-mouth like geometric feature with a rounded turn radius. The inflation of the rubber lip can be achieved by defining a ported flow channel to divert and use the air from the bypass duct during the aircraft glide before touchdown for the landing run. With such a controlled auto-inflation mechanism using air in the bypass duct, there will be no additional bleed air related penalty on the engine performance. A complete Failure-Mode-Effect-Analysis study for the rubber lip design is being considered to quantify the criticality of failure on the aircraft system. However, before the complete study in this preliminary design exploration stage, it is posited that the impact of the rubber lip functional or structural failure on aircraft is likely to be non-critical because: 1. the lip is conceived to be made from polymeric rubbers reinforced by support spars and restrained along the nacelle surface. So, likelihood of free component release in flight is low. 2. Functional failure during landing run, such as a puncture in the rubber is not likely to impact aircraft safety because it would only entail a rapid deflation of the rubber lip. The likelihood of puncture could also be minimized by multi-ply synthetic polymer designs.

To understand the design space of the rubber lip, the performance of a wide range of rubber lip rounding radii values was explored. The geometric parameters for the design variants are decided based on certain design constraints to ensure that the aircraft nominal performance is not significantly affected. From these studies, three different design options that would convey the effects of the design dimensions on the reverse thrust flow physics are described in this paper. A sketch of the three exemplary geometric implementations are shown in Figure 4.

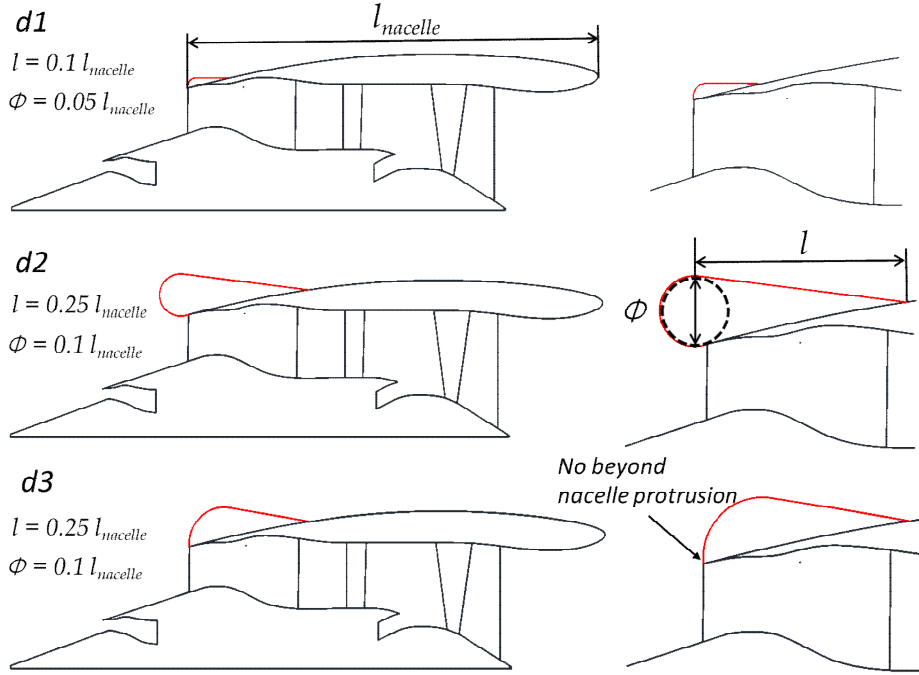


FIGURE 4: DESIGN VARIANTS OF THE RUBBER LIP CHOSEN FOR EXPLAINING THE EFFECT ON REVERSE FLOW

The exemplary design variants explore the effect of the rubber lip by considering two rounding radii, 5% ('d1' design) and 10% ('d2' design) of nacelle axial length. A turning radius of more than 10% nacelle length would result in a thick trailing edge at the uninflated condition and affect nominal forward flow operation. The length of the rubber lip is fixed at an upper limit of 25% of nacelle length to minimize the weight and thickness of support spars that may be required to define or bolster the inflated shape. The length restriction would also ensure that the inflation volume of the rubber lip is not prohibitively large, and hence the air required for inflation would also not be significant. Another variant of the larger radius design ('d3' design), in which the turn radius does not extend beyond the nacelle trailing edge is also discussed. This variant is explored to compare the performance with the 'd2' design variant that has an overhang in the turning radius. For the smaller rounding radii, the upper surface of the lip, which connects the rounding radii with the nacelle surface, is defined parallel to the engine axis. For both the larger rounding radii, the upper surface has a minor upward deflection of $<10^\circ$ with reference to the engine axis because of the length restriction.

The design variants of the rubber lip are installed on to the integrated airframe-engine-VPF model. For the 'd1' variant, full annular coverage with the inflated lip except for the region occupied by the pylon, $350^\circ - 10^\circ$, is possible; 0° reference at the pylon center line. However, for the larger radii, 'd2' and 'd3' variants, full annular coverage is not possible because of the interference from the slats. Therefore, to accommodate the slat interference and the pylon obstruction, both the larger variants occupy the annular extents ranging from 45° to 315° . Exploring the effect of the rubber lips in the full airframe-engine model mimics realistic design implementation scenarios in the aircraft that would not have been possible in isolated engine models. The installed rubber lip in the integrated model is

shown by using the 'd2' design variant in Figure 5 to highlight the installation related compromises. The aircraft models with the inflated rubber lip variants are discretized using similar unstructured grid topology parameters as in the baseline airframe model. In all the rubber lip variants, the engine internal flow path representation is same as in the baseline model. The reverse thrust flow field with the different inflatable rubber lip design variants are generated for the aircraft landing run thrust reverser engagement regime using similar computational solution methods as in the baseline integrated model at the same VPF operational stagger angle setting and rotational speed. The change in the reverse thrust flow field with the rubber lips is discussed in the next section.

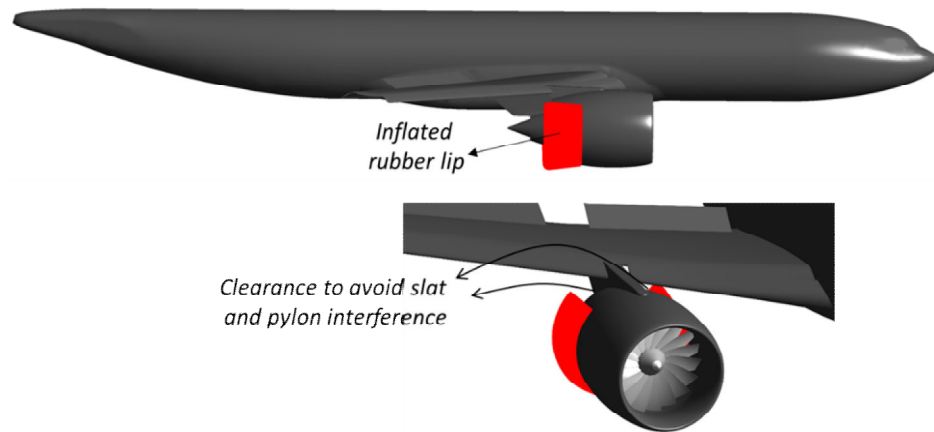


FIGURE 5: 'd2' DESIGN VARIANT IN INTEGRATED MODEL SHOWING INSTALLATION FEATURES

Inflatable Rubber Lip in Reverse Flow @110 knots

The flow field change with the inflated rubber lip design variants is discussed by considering an aircraft landing speed of 110 knots, which is representative of the general changes at other speeds. The effect of the design modification is felt on the external flow field near the engine exit, the reverse flow entering at the bypass nozzle exit and the subsequent development of the reverse flow within and out of the engine. The combined composite changes in the reverse thrust flow field are visualized by using streamlines projected on to a mid-engine surface plane that passes through the engine top-bottom centerline as shown in Figure 6 for the baseline configuration and the rubber lip design variants.

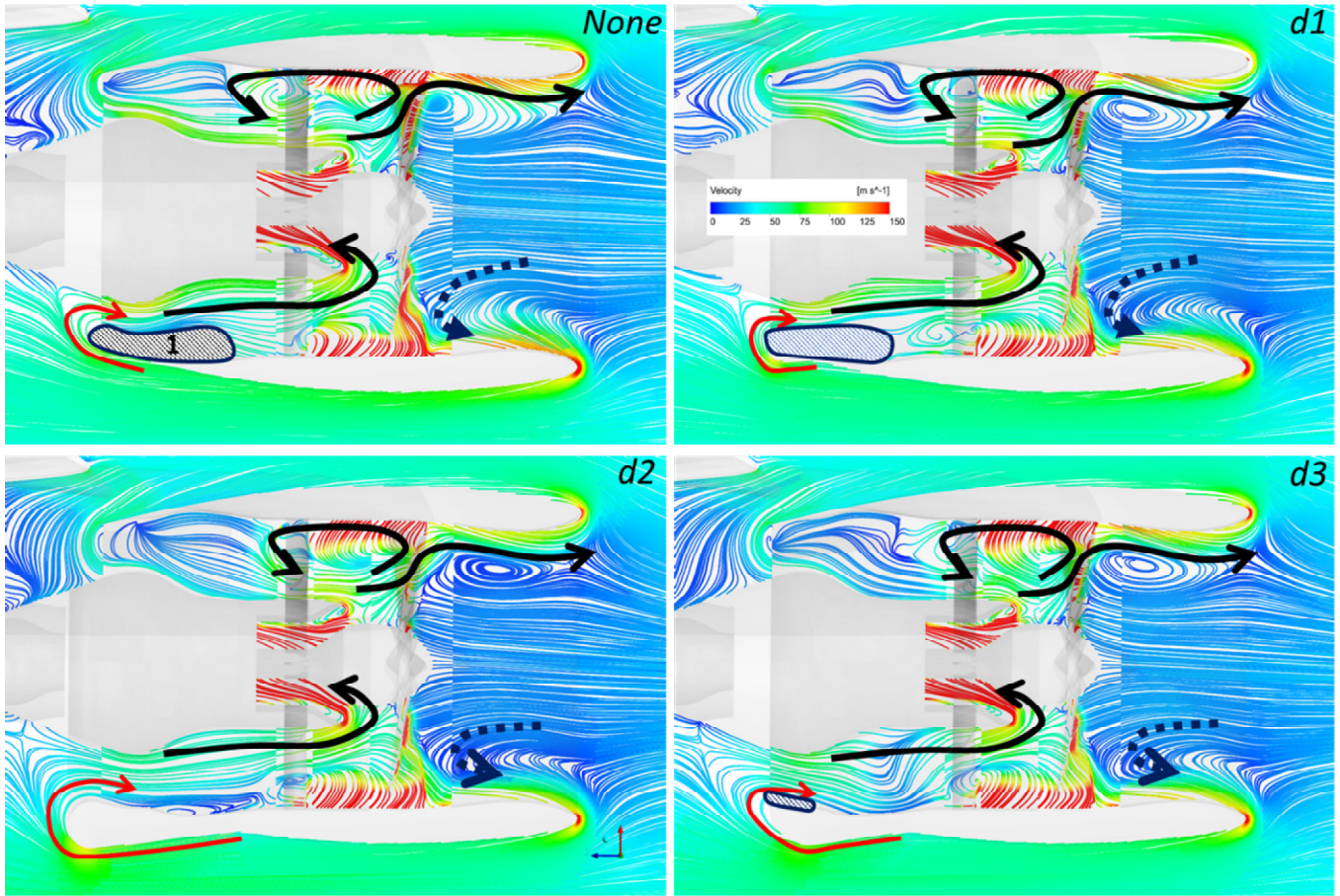


FIGURE 6: ENGINE MID SURFACE PROJECTED STREAMLINES FOR BASELINE AND RUBBER LIP VARIANTS SHOWING CHANGE IN FLOW FEATURES

The development of the reverse flow within the engine internal flow path after the 180° turn of the washed-down flow, which leaves the separated flow region marked '1' at the bypass nozzle exit is also shown in the streamline plots of Figure 6. The general features of this internal flow development are similar in the baseline architecture and in the rubber lip design variants; the reverse flow that enters in at the bypass nozzle exit develops along the bypass nozzle duct, through the Outlet Guide Vanes (OGV) and thereafter, a fraction turns into the core engine at the splitter and the remaining fraction enters the VPF passages. Within the VPF, the reverse stream meets the free stream in a shear layer and is centrifuged outward radially due to the closed hub aerofoil passages and the back pressure of the free-stream in the spinner region. A portion of this centrifuged reverse stream escapes out of the fan nominal outlet towards the engine exit, passes through the OGV where it loses its momentum, and rejoins the reverse flow from the bypass nozzle exit. This re-circulation zone within the engine is marked '2' in Figure 6 and can include fluid particles that have passed multiple times through the fan passages. Another portion of the centrifuged reverse stream escapes out from the fan nominal inlet as discrete jets from the different aerofoil passages due to work addition. This reverse flow out from the fan inlet entrains the free stream in the nacelle inlet regions and flows out

towards the nacelle inlet, marked '3' in Figure 6. This flow is washed-down by the free stream at the nacelle inlet lip towards the engine exit regions. Further details about the internal flow field and the fan flow features in reverse thrust are discussed in the work describing the fan flow field by the authors [11].

In the inflatable rubber architectures, the washed-down reverse stream from the nacelle lip is guided into the engine exit regions at the nacelle outer surface. The radial turning-in of the reverse flow as it comes under the influence of the fan suction changes the properties of the reverse stream flow ingested into the engine at the bypass exit. The effect of the rubber lip design variants on the features of the reverse thrust flow field, marked with the identifiers in Figure 6, as compared to the baseline are described below:

1. Separation at Bypass Nozzle Exit, '1' – the reduction of this separation zone that acts like a blockage to the development of the reverse flow into the engine is the stated objective in the implementation of the rubber lip. The axial velocity contours at the bypass nozzle exit plane for the baseline case and the rubber lip design variants are shown in Figure 7 to highlight the circumferential variation across the designs. These plots complement the projected streamlines in Figure 6 and aid in understanding the flow field changes with a clearer picture of the installation effects.

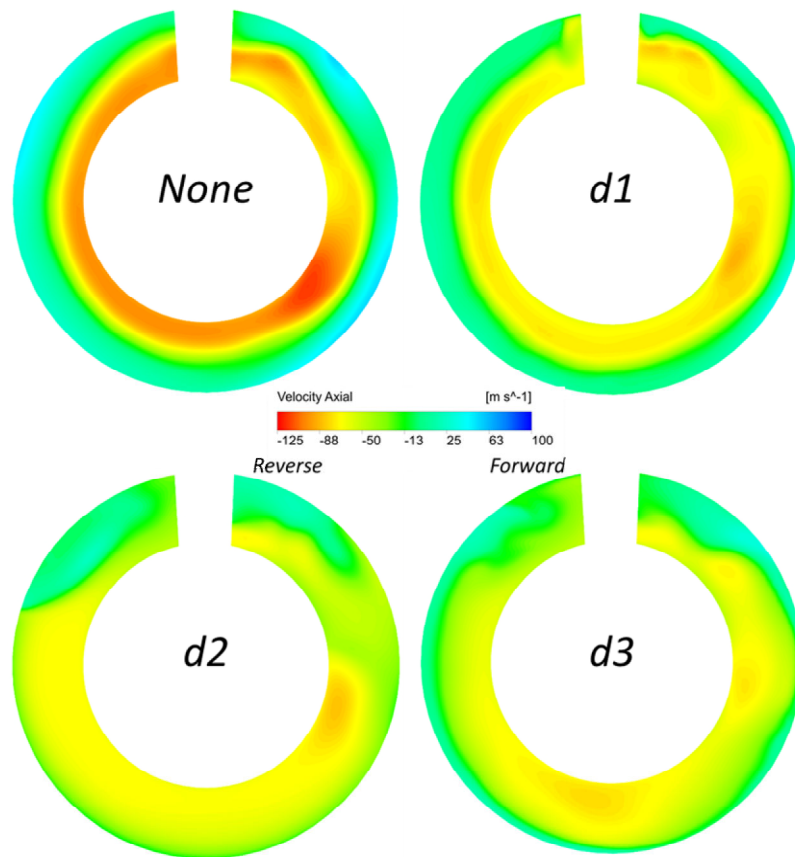


FIGURE 7: AXIAL VELOCITY CONTOURS AT BYPASS EXIT PLANE FOR BASELINE AND RUBBER LIP VARIANTS

In the 'd1' variant, even with a small deflection, the velocity of the reverse stream into the engine is reduced because of the flow turning through a larger radius as compared to the sharp turn in the baseline. However, the turning radius is not sufficient to significantly affect the radial extent of the bypass nozzle lip separation, except for some minor stream-tube stretching associated with the reduction in flow velocity. A minor reduction in the outward protrusion of the separation zone, as seen in the axial extent of feature '1' in Figure 6 - 'd1', is observed because of the increased radius turn into the engine.

In the 'd2' variant, the larger turning radius is sufficient to get rid of the bypass nozzle lip separation, as observed from the streamline and axial velocity contours. In the top annular regions, where the 'd2' rubber lip cannot be installed, there is a reduction in the amount of reverse stream entering the engine because of the obstruction in the rubber lip edge, pylon and the extended slat regions. Moreover, in this unguided flow turn region where there is no rubber lip, the extent of separation zone is like that of the baseline architecture.

In the 'd3' variant, even though the turning radius is similar to the 'd2' variant, a minor separation zone that occupies nearly 5% tip annular area around the circumference is observed. This is because in the 'd3' variant, since there is no protrusion beyond the nacelle trailing edge, the guidance imposed by the turning radius ends at the nozzle lip, which reduces the effective radius of the turn and consequently a region of small separation near the tip is observed as the reverse flow enters the engine. Other than this minor tip separation, the extent of which is significantly lower than the separation in the baseline architecture, the reverse stream properties entering into the engine are similar to the 'd2' variant. The obstruction to the reverse flow guidance in the top annular regions, where there is no guidance imposed by the rubber lip, is also observed in the 'd3' variant.

In both the 'd2' and the 'd3' variants, and to a lesser extent in the 'd1' variant, the stretching of the reverse flow stream tube because of the larger radius of the turn results in a reduction of the axial velocity at the bypass nozzle exit. The signature of increased mass flow ingestion observed on the right side of the axial velocity contour plot because of the VPF suction acting on the slower moving fluid in the pylon obstructed wing in-board region is observable in both the baseline and in the rubber lip variants.

In the 'd2' and 'd3' rubber lip architectures, the effect of the flow field change because of the more effective capture and guidance of the reverse flow streamlines results in a reduction of the bypass nozzle lip separation, reduces the blockage to the reverse flow ingress into the engine internal flow path, causes the reverse stream to occupy a larger flow area at the bypass nozzle exit and results in an increase in the reverse stream mass flow at the same VPF operating point. At the landing speed of 110 knots, the increase in reverse stream mass flow, as compared to the baseline, for the 'd2' variant is ~34% and the 'd3' variant is ~19%, while for the 'd1' variant no significant changes are observed. The mass flow increase is lower in the 'd3' variant as compared to the 'd2' variant because the minor separation zone occupies 5% of the tip annulus area that has a significant impact in the flow ingestion area. The increase in the reverse

stream mass flow affects the subsequent development of the reverse flow within the engine, as can be observed from the changes described below in the other the two marked flow features, '2' and '3' of Figure 6.

2. Internal Recirculation Zone, '2' – The axial extents of the bypass duct occupied by the internal recirculation zone '2' in the 'd2' and 'd3' rubber lip architectures are reduced, while the d1' variant does not indicate any significant change, compared to the baseline as observed from the streamline plots of Figure 6. The reduction in the axial extent is observed by a reduction in the location relative to the OGV blade row exit at which the recirculating flow turns-around to join the reverse flow from the bypass nozzle exit. The difference in signature of the extent to which the recirculation zone extends into the bypass duct is shown by the axial velocity contours at a plane that is 25% axial chord downstream of the OGV blade row in Figure 8 for the baseline case and in the rubber lip variants. In the axial velocity contours, the blue striations in the outer annular regions indicate the portion of the recirculation zone that flows towards the engine exit, and the inner annular regions indicate the reverse flow towards the VPF passages. The striations in the outer annular regions are caused by the wake signature of the recirculation flow passage through the OGV blade row. The inner annular region occupied by the reverse flow indicates a large vacuous flow region, generally toward the bottom regions of the plane, because of a combination of the pylon strut wake, reduction in flow near the top pylon obstructed regions and the swirling development of flow in the bypass duct. The circumferential variation in the flow signatures at the OGV exit plane because of the advection of the variations from the bypass nozzle exit plane is also noted in Figure 8.

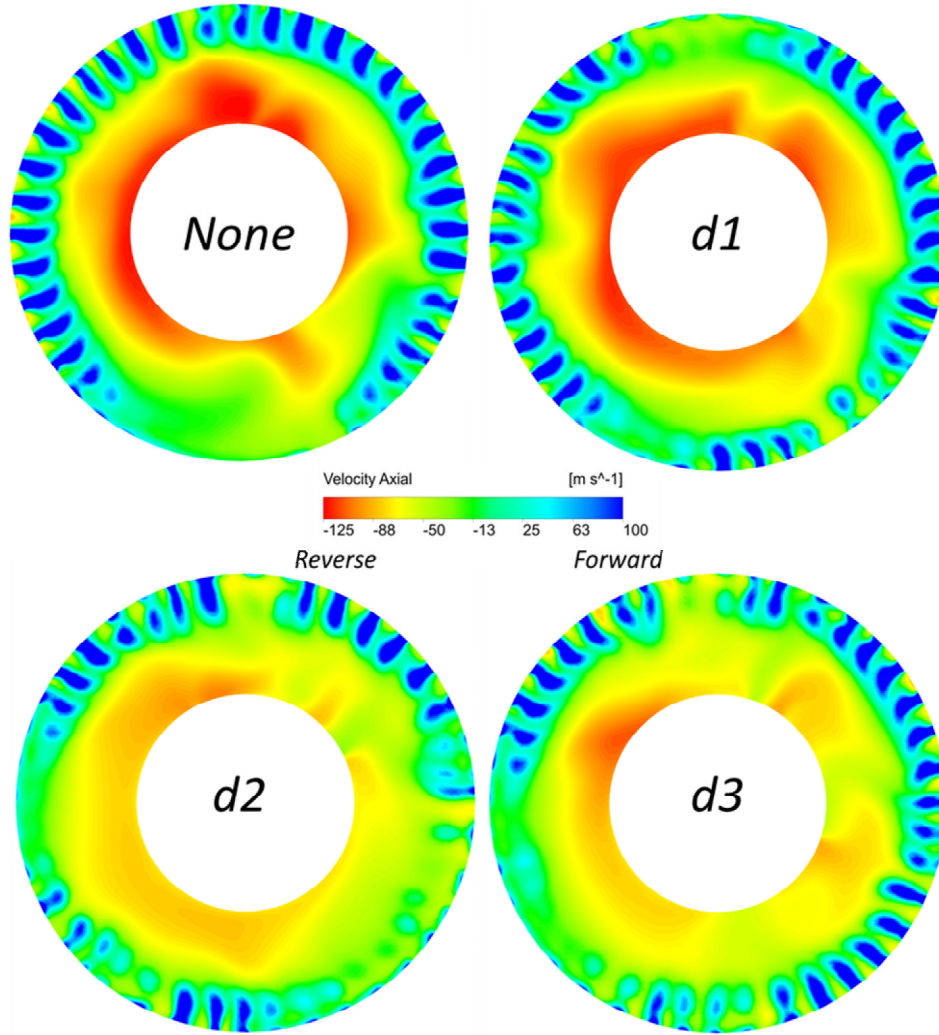


FIGURE 8: AXIAL VELOCITY CONTOURS AT OGV EXIT PLANE FOR BASELINE AND RUBBER LIP VARIANTS

It is noticed that the number of blue striations and the amount of fluid, as indicated by the values of the axial velocity and the thickness of the striations, is lower in the 'd2' variant as compared to the baseline configuration. Similarly, the 'd3' variant also indicates a corresponding reduction in this flow signature, though not to the extent of the 'd2' variant. However, the 'd1' variant does not exhibit significant changes from the strong, full annular, striation signature as in the baseline configuration. The reduction in the flow signatures of the recirculation flow in the outer annular regions for the 'd2' and 'd3' variants demonstrate that a major portion of the recirculation flow has turned back to join the reverse flow in the inner annular regions before it reaches the fixed reference OGV exit plane, thus indicating an axial reduction in the extents of the internal recirculation zone '2'. This reduction in the extents occupied by the internal recirculation zone is because of the increasing momentum of the reverse stream from the bypass nozzle exit because of the increase in the reverse stream mass flow. The increased reverse flow momentum pushes the recirculation region towards the fan and reduces its penetration into the bypass nozzle duct, as marked in the streamline plots of Figure 6.

3. Reverse Flow Out of Fan Inlet, '3' – A fixed portion of the reverse flow from the bypass nozzle exit turns 180° at the splitter edge to feed the core engine in the baseline cases and in the rubber lip design variants because the core engine operating point is the same for all the cases. The amount of reverse flow from the fan nominal outlet tip regions that sets up the internal recirculation zone '2' is also similar in all the cases because it is controlled by the VPF passage geometry and rotational speed, which also remain the same in all cases. Therefore, the increase in the reverse stream mass flow at the bypass nozzle exit in the 'd2' and 'd3' rubber lip architectures is conveyed to the reverse flow out of the fan nominal inlet to the nacelle inlet regions. The reverse flow out of the inlet in the 'd1' variant remains like that of the baseline configuration. The increase in the reverse flow out of the fan inlet in the 'd2' and 'd3' variants can be observed by the larger annular extent occupied by the red marker '3' in the streamline plot of Figure 6.

The stronger reverse flow out of the fan in these variants also influences the entrainment of the freestream in the nacelle inlet regions. In the 'd2' variant, the increase in the momentum of the reverse stream skews the shear layer with the freestream towards the fan inlet. The consequent dominance of the reverse stream momentum in the nacelle inlet regions causes a minor reduction in the amount of freestream flow entering in through the nacelle inlet and therefore a more effective entrainment roll-up of the freestream to join the reverse stream towards the nacelle lip. The bolstered reverse stream at the nacelle lip causes it to penetrate further axially outward from the engine before it is washed-down by the freestream flow, as can be observed from the flow turn arrows around the nacelle inlet lip. After the washing down of the reverse flow as well, the radial extents occupied by the turned back flow streamlines is larger in the increased reverse flow cases, as observed from the thickness of washed-down flow from the flow arrow outside the engine near the nacelle inlet. Therefore, it is noticed that the increase in the reverse stream mass flow directly leads to a more drag generating external flow field that would additionally aid in increasing the amount of reverse thrust generated by the system. These changes in the nacelle inlet and lip region are relatively less pronounced than the 'd2' variant in the 'd3' variant. On the other hand, in the 'd1' variant, these changes are not observed, and the flow field is similar to the baseline

Effect of Landing Speed

The general trends of the reverse thrust flow field change for the highlighted flow features in the rubber lip architectures observed at the 110 knots landing speed are also observed for the complete aircraft landing run from 140 knots to the thrust reverser shut down velocity of 40 knots. A representative illustration of the landing speed effect on the axial velocity contours at the bypass nozzle exit is shown for the best performing 'd2' variant and the baseline configuration in Figure 9. The axial velocity contours at the bypass nozzle exit are chosen to illustrate the effect because the reduction of the separation region at this exit plane and the consequent increase in the reverse stream mass flow drives the subsequent changes within the engine internal flow path.

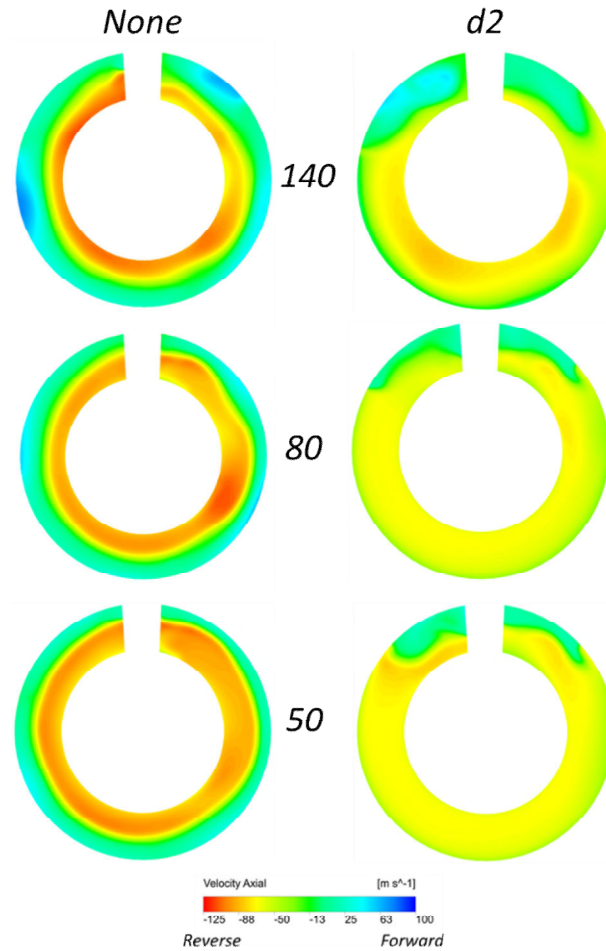


FIGURE 9: EFFECT OF LANDING SPEED ON ‘d2’ VARIANT SHOWN WITH AXIAL VELOCITY CONTOURS

The axial velocity contours in Figure 9 indicate that the turning radius of the ‘d2’ variant is sufficient to reduce the outer annular separation of the baseline configuration throughout the aircraft landing run. As the aircraft landing speed reduces, the bulk velocity of the washed-down stream which turns into the bypass nozzle exit reduces, and consequently the rubber lip is effective in reducing the extent of the separation region. The extent of the reverse flow reduction because of the obstruction due to the pylon and the slat also reduces with reduction in the landing speed, because a relatively slower moving fluid in the rubber lip edge-pylon-slat region comes under the influence of the VPF suction. At higher landing speeds however, it is observed that a larger portion of the relatively faster moving fluid in the obstructed flow region manages to escape the fan suction, skirts over the upper portion of the slat and proceeds downstream towards the wing. The landing speed driven changes to the ‘d3’ variant are similar to those of the highlighted changes for the ‘d2’ variant, but for the presence of the minor tip annular separation at all landing speeds like that highlighted at 110 knots. The ‘d1’ variant is not observed to be having a significant effect at other landing speeds as well, except for the minor stream tube stretching at all

landing speeds like at 110 knots. The effect of the landing speed on the flow features within the engine relating to the extent of the internal recirculation zone and the reverse flow out of the fan are also like the changes described at 110 knots.

Effect of VPF Setting

In the present work, the baseline configuration and all the rubber lip architectures are considered to operate in VPF reverse thrust mode with the same ζ_1° stagger angle setting, which is within $\pm 5^\circ$ from the 90° through feather rotation of the VPF aerofoils, and at a rotational speed that is representative of the engine landing operating point. The choice of the ζ_1° stagger angle setting is based on the wide operating pressure ratio range of the VPF reverse flow characteristics. Typically, the change in the stagger angle setting is restricted to $\pm 5^\circ$ from this reference stagger angle because of geometric constraints, and to avoid excursions away from the wide reverse flow operation region. The installed reverse thrust behavior in this zone of stagger angle change is observed to have only a minor effect on the overall reverse thrust flow field. This is because any reduction of the stagger angle that corresponds to an opening of the airfoil passages, results in an opening at both the nominal fan inlet and outlet regions. Therefore, any notional advantage of handling higher reverse stream mass flow from the outlet, as expected from an isolated VPF only characteristics, is offset by an increased freestream penetration from the inlet that increases the back pressure and prevents any significant increase in the reverse flow out of the fan inlet. Since the reverse flow out of the fan inlet remains similar across the reverse flow stagger angle zone, the general reverse thrust flow field remains similar as well.

The VPF rotational speed influences the extent of fan suction felt on the engine exit regions and consequently on the amount of reverse flow entering the engine. The change of the VPF rotational speed within $\pm 10\%$ of the reference rotational has a direct near-linear effect on the amount of the reverse flow into the fan. For instance, at the same landing speed, at a lower VPF rotational speed, the shear layer interaction between the freestream and the reverse stream is dominated by the freestream momentum and the extent of reverse stream spread around the engine is reduced. The opposite changes are observed at a higher VPF rotational speed. The changes in the spread of the reverse stream with change in VPF rotational speed does not significantly affect the general features of the external and the internal reverse thrust flow field.

Therefore, for changes within $\pm 5^\circ$ of stagger angle setting or within $\pm 10\%$ of the rotational speed, the ingress of the reverse flow into the engine occurs through a 180° turn at the bypass nozzle, which results in a separated blockage zone at the bypass nozzle exit plane. Within this operational setting window, which would represent typical bounds of the VPF setting during the landing run, the reduction of the bypass nozzle exit separation by the increase in the turning radius in the rubber lip architecture remains effective because the general external flow field features remain similar to the baseline configuration for each case. It is emphasized that the increase in the reverse stream mass flow achieved in the rubber lip architectures occurs at the same fan rotational speed because of the removal of

the blockage at the bypass nozzle exit. The removal of the blockage may be considered analogous to the opening of an inlet throttle valve placed before a fan, which would result in an increase in the mass flow through the fan at the same rotational speed.

Effect on Reverse Thrust Parameters

The increase in the reverse stream mass flow ($\dot{m}_{rev}$) normalized with a fan design reference mass flow ($\dot{m}_{ref}$), as compared to the baseline configuration for the best performing ‘d2’ variant of the rubber lip architecture during the complete aircraft landing run is shown in Figure 10. The reverse stream mass flow – landing speed line of the ‘d3’ and the ‘d1’ variants of the rubber lip architecture lie between the two lines shown in the plot. At the same VPF reverse flow setting, an increase in the reverse stream mass flow is observed in both cases with a reduction in the aircraft landing speed. This is because the fan suction is acting on a slower moving fluid at the engine exit which causes a larger amount of flow to turn into the engine. The ‘d2’ variant indicates an increase in reverse stream mass flow ranging from ~47% to ~18% in the 140 knots to 40 knots landing speed range. The increase in mass flow reduces with the landing speed because the extent of separation zone in the baseline architecture reduces with the landing speed due to the lower bulk velocity of the washed-down stream. Therefore, at lower speeds the scope for improvement of the blockage with the rubber lip variants reduces.

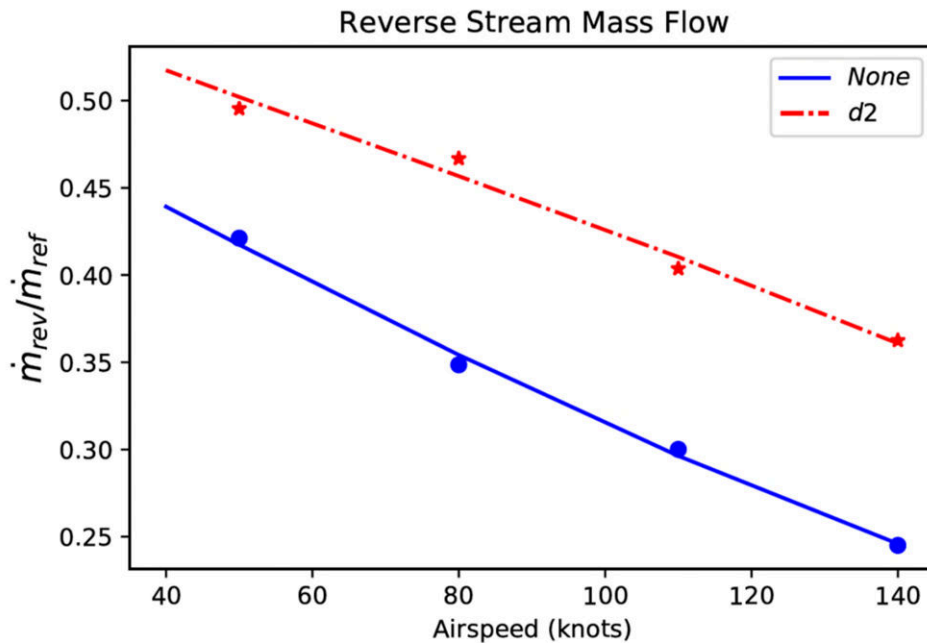


FIGURE 10: INCREASE IN REVERSE STREAM MASS FLOW WITH ‘d2’ RUBBER LIP VARIANT

At notional static conditions, where the thrust reverser is not used, both the baseline and rubber lip architectures will handle similar amounts of reverse flow. This is because most of the reverse flow into the engine at static conditions is captured from the regions behind the engine exit and not through a 180° turn at the bypass nozzle lip as in the installed dynamic conditions. In such notional static conditions, the flared nozzle ‘exlets’ would be effective in guiding the flow into the engine. However, these ‘exlets’ would not be as

effective in dynamic conditions because the flare in the nozzles would divert the flow away from the influence of VPF suction in the engine exit regions. The inflatable rubber lip architectures on the other hand are conceived based on the installed dynamic reverse thrust flow field and have maximum beneficial impact in the active thrust reverser engagement regime of 140 to 40 knots during the aircraft landing run. This observation also demonstrates the case for conceiving design improvements in the actual installed dynamic conditions rather than in simplified static conditions as was usually done.

The increase in the amount of reverse stream mass flow in the rubber lip architectures directly contributes to a proportional increase in the engine reverse thrust portion of the decelerating force on the airframe during the landing run. Moreover, the effect of the additional reverse stream mass flow penetrating farther around the engine in the rubber lip architectures, results in an increase on the aircraft external drag component of the decelerating force on the airframe. A near field integral based computation of the additional drag force component of the total decelerating force indicates an increase in the range of 7% to 3% for the 'd2' variant in the 140 knots to 40 knots landing speed range.

Additionally, the reduction in the separation region with the rubber lip architecture results in a uniform total pressure distribution with a ~2% higher average value at the bypass nozzle exit at each aircraft landing speed. The higher total pressure value of the reverse stream consequently causes the core engine feed flow that turns 180° at the splitter edge to be at a higher total pressure as compared to the baseline configuration because in both the cases the total pressure loss in the bypass duct is similar. Therefore, a minor 2% improvement in the pressure recovery into the core engine, which improves the core engine operability, is also observed as a secondary improvement in using the rubber lip architecture. Moreover, the increased uniformity of the total pressure distribution around the annulus also results in a minor ~1% improvement in the circumferential total pressure distortion index into the core engine. The radial total pressure distortion index into the core engine is not significantly affected because the negative effect of the 180° turn of the larger amount of reverse stream is balanced by the lower velocity of the reverse stream flow because of stream tube stretching. Therefore, the rubber lip architectures present a feasible design improvement that holds potential to improve the engine reverse thrust along with certain secondary improvements to the overall operability of the system.

Applicability to Other Airframe-Engine-VPF Designs

The present study has considered a typical 300 passenger commercial airframe with two 40000 lbf geared, 14 design bypass ratio turbofan engines. It is for such large diameter, high bypass ratio applications that VPF in reverse thrust is a technology enabler for reducing the overall aircraft mission fuel burn. In these cases, optimal forward flow pressure ratios of VPF remain below 1.3 for maximum engine thermodynamic efficiency. Moreover, since the typical forward flow operation is the primary operational mode of the VPF, the design optimization of the fan aerofoils in terms of flow coefficient and loading distributions is still carried out for the nominal

operation. In the VPF design used in this study, no special additional design constraints have been imposed on the baseline VPF design to aid in the reverse flow operation. The reverse flow mode operation of such typical forward flow optimized VPF designs in installed dynamic conditions is used in the present study to guide the improvement of the reverse thrust flow field using rubber lip architectures. The reverse thrust flow field behavior improvement with the rubber lip architectures depend upon the development of the engine internal flow by a 180° turn and the flow bulk velocity at the engine exit regions. The flow bulk velocity at the exit regions is primarily dominated by the freestream velocity and to a lesser extent by the reverse flow velocity out of the fan inlet. The reverse flow velocity out of the fan inlet in turn depends on the fan pressure ratio and the reverse flow setting, which remain in similar ranges for typical reverse flow capable VPF designs. Therefore, the improvements in the reverse thrust flow field observed with the inflatable rubber lips can be read across to other similar low pressure VPF designs in reverse flow. For this reason, the quantitative improvement in the reverse stream mass has been normalized with the fan design mass flow.

The engine diameter of the representative 40000 lbf engine inlet diameter considered in this study is ~110 inches, the bypass nozzle area is ~0.9 square inches. Standard scaling laws can be used to read across the results to other engine and equivalent airframe installations. The dimensions of the inflatable rubber lip architectures have been normalized with the nacelle length. The discussion of the flow field has used the aircraft landing speed in knots and axial velocity contours to describe the reverse thrust flow field in typical conventional aircraft landing performance parameters and to clarify the flow physics in bi-directional flow within the engine. The analysis has been carried out in ISA, SL conditions and corresponding Mach number corrections can be done to read across the results for other design cases. Additionally, it is emphasized that the rubber lip architectures have been characterized for all possible operating conditions during the aircraft landing run, except crosswind and gust.

CONCLUSIONS

VPF reverse thrust operation during the typical aircraft landing run in the baseline configuration indicates a separation at the bypass nozzle exit, which affects reverse flow entry into the engine. The inflatable rubber lip architecture is demonstrated as a design modification that can remove the separation and significantly increase the amount of reverse flow through the engine in realistic installed and dynamic conditions of the complete aircraft landing run. The major outcomes from this study are:

1. A detailed design space exploration, from which three exemplary designs are highlighted for discussion in this work, has provided the geometric dimensions around which rubber lip designs can be optimized. A representative rubber lip design with a turning radius of 0.1x nacelle length, installation length of 0.25x nacelle length and an overhang in the turning radius beyond the trailing edge, that has been demonstrated to improve the reverse flow behavior, is suggested as a possible initial choice for implementation and further refinement.

2. The suggested rubber lip dimensions demonstrate a significant improvement in the amount of reverse flow handled while respecting constraints on ease of flushed storage along the optimized nacelle aerodynamic surface during normal operation, deployment without interference of other airframe surfaces, air inflation volume and complexity of support structures. The weight penalty associated with the inflatable rubber lip is not significant because the structure can be designed structurally sound with collapsible support struts, which can stretch out portions of a low weight synthetic polymer rubber sheet.

3. An overhang in turning radius region beyond the nacelle trailing edge is preferable to restricting the turning radius at the trailing edge because of the disproportionate effect that even a small separation at large outer annular radii can have on the flow area.

4. The increase in the reverse stream mass flow with the rubber lip architectures occur at a fixed VPF operating point. Since the reverse thrust magnitudes depend on the amount of reverse flow, the required levels of reverse thrust with the rubber lips could be developed by operating the VPF at more benign low power settings. This could lead to a further second order improvement in the overall airframe decelerating force because operation at lower power settings would also lead to a lower core forward thrust.

5. The importance of using the installed VPF reverse thrust behavior at representative aircraft landing speeds in conceiving design improvements and modifications is emphasized. The traditional methods of conducting the design studies at static uninstalled conditions may be misleading and may even lead to penalties in actual operating conditions.

Further investigation of design modifications and alternative architectures that can address and improve specific aspects of the installed reverse thrust flow field during the aircraft landing run is currently underway to identify a composite system design that can maximize the benefits obtained from the use of VPF for reverse thrust.

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NOMENCLATURE

Abbreviations

ADP	Advanced Ducted Propulsor
GCI	Grid Convergence Index
ISA	International Standard Atmosphere
OGV	Outlet Guide Vane
RANS	Reynolds Averaged Navier-Stokes

SL	Sea Level
SST	Shear Stress Transport
VPF	Variable Pitch Fan

Symbols

y^+	non-dimension wall distance
$d1, d2, d3$	design identifiers
E_D	Engine diameter
k	turbulence kinetic energy
l	rubber lip length
$l_{nacelle}$	nacelle length
$\dot{m}$	mass flow
ζ	stagger angle
ϕ	lip diameter
ω	specific dissipation rate

Subscripts

ref	reference
rev	reverse

REFERENCES

- [1] Krishnan, G., Perullo, C. and Mavris, D.N., 2013. An Assessment of Relative Technology Benefits of a Variable Pitch Fan and Variable Area Nozzle. In 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference (p. 3604).
- [2] Yang, X., Tang, H. and Chen, M., 2018. Performance Modeling and Optimization Assessment of Variable Pitch Fan for Ultrafan Engine. In 2018 Joint Propulsion Conference (p. 4400).
- [3] Mazzawy, R.S., 2010, October. Performance Study for the Benefits of a Variable Pitch Composite Fan. In ASME Turbo Expo 2010: Power for Land, Sea, and Air (pp. 37-45). American Society of Mechanical Engineers.
- [4] Joksimovic, A., Duplaa, S., Bousquet, Y. and Tantot, N., 2018. Performance prediction methodology and analysis of a variable pitch fan turbofan engine. Aeronautics and Aerospace Open access Journal, 2 (6), pp. 394-402, 10.15406/aaoaj.2018.02.00071. HAL-02074473.

- [5] Schaefer, J.W., Sagerser, D.R. and Stakolich, E.G., 1977, "Dynamics of high-bypass-engine thrust reversal using a variable-pitch fan," NASA Scientific and Technical Information Branch, NASA TM X-3524.
- [6] Sagerser, D.A., Schaefer, J.W. and Dietrich, D.A., 1976. Reverse-thrust technology for variable-pitch fan propulsion systems. NASA Scientific and Technical Information Branch, N 78-24070.
- [7] Vier, W.F., 1975. Quiet, clean short-haul experimental engine (QCSEE) test results from a 14 cm inlet for a variable pitch fan thrust reverser. NASA Scientific and Technical Information Branch, NASA CR-134867.
- [8] Hobbs, D.E., Neubert, R.J., Malmborg, E.W., Philbrick, D.H. and Spear, D.A., 1995, "Low Noise Research Fan Stage Design," NASA Scientific and Technical Information Branch, NASA-CR-195382.
- [9] Jeracki, R.J., 2006, Comprehensive report of fan performance from duct rake instrumentation on 1.294 pressure ratio, 806 ft/sec tip speed turbofan simulator models, NASA Scientific and Technical Information Branch, NASA TM 2006-213863.
- [10] Williams, T.S. and Hall, C.A., 2019. Reverse Thrust Aerodynamics of Variable Pitch Fans. Journal of Turbomachinery, 141(8), p.081008.
- [11] Rajendran, D.J. and Pachidis, V., 2019. Fan Flow Field in an Installed Variable Pitch Fan Operating in Reverse Thrust for a Range of Aircraft Landing Speeds. Journal of Engineering for Gas Turbines and Power, 141(10).
- [12] Rajendran, D.J. and Pachidis, V., 2020. Flow Distortion into the Core Engine for a Variable Pitch Fan in Reverse Thrust Mode. Proceedings of ASME Turbo Expo 2020: Turbomachinery Technical Conference and Exposition, GT2019-14174, June 22-26, 2020, London, England.
- [13] Rajendran, D.J., Bentley, D.J., Aguirre, H.A., Tunstall, R., and Pachidis, V., 2020. Development of a Research Model to Study the Operability of a Variable Pitch Fan Aero Engine in Reverse Thrust. GPPS-CH-2020-43, Proceedings of Global Power and Propulsion Society, GPPS Chania20, September 7-9, 2020.
- [14] Vassberg, J.C., Roman, Dino, Dehaan, Mark. 2017. Fan Cowl With A Serrated Trailing Edge Providing Attached Flow in Reverse Thrust Mode. US Patent US20170801105.
- [15] Philippart, G. 2016. Nacelle Optimisee Pour Un Turboreacteur Comprenant Une Soufflante A Calage Variable Disposant D'un Calage D'inversion De Poussee. France Patent FR20160059344.
- [16] Lecordix Jean Loic, Herve, Bordoni, Nils, Kubiak Guillaume, Patrice, Lekordi Zhan Loik, Erve. Turbomachine Comprising A Plurality of Fixed Radial Blades Mounted Upstream of the Fan. France Patent FR20120057742.
- [17] Ansys® CFX, Release 18.2, Theory Guide, CFX, ANSYS Documentation, Chapters 1 and 2, ANSYS, Inc.
- [18] Roache, P.J., (1993). A method for uniform reporting of grid refinement studies. ASME-PUBLICATIONS-FED, 158, pp.109-109.



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