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ON THE FLOW PHYSICS DURING THE TRANSITION OF A VARIABLE PITCH FAN FROM NOMINAL OPERATION TO REVERSE THRUST MODE

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ABSTRACT

The flow field during the transition of a VPF from nominal operation to reverse thrust mode at typical 'Approach Idle' engine power setting and aircraft touchdown speed of 140 knots is described in this work. An integrated airframe-engine-VPF research model that features a future 40000 lbf geared high bypass ratio engine installed on a twin-engine airframe in landing configuration is used to explore the flow field in a fully transient URANS simulation with imposed wall motion. A novel methodology that implements an adaptation of a mesh displacement equation to mimic the fan blade aerofoil rotation is developed. The implementation of this method with gradual, small step deformation along with an automated mesh update routine enables a high quality, near 'real-time' simulation of the complete transition.

The flow field during transition is characterised by the evolution from full typical forward flow through the engine to the development of massive recirculation regions at the feather pitch setting and finally to development of a reverse flow from the bypass nozzle to the fan passages. In the paper, the transient development of the various flow features through different stations of the engine flow path apropos the fan blade aerofoil rotation to reverse thrust mode are discussed in detail in the paper. Also, the temporal development of the mass flow ingested through the engine, airframe decelerating force and distorted flow at the core engine inlet are described. A hitherto unresolved fan power peaking during the middle of the transition and higher power requirement at reverse thrust mode is captured. The effect of fan rotational speed in terms of engine power setting and the aircraft touchdown velocity on the transition flow physics is explored. A comparison

of this fully transient approach with discrete steady-state runs for different stagger angle settings is presented. The flow physics during transition to reverse thrust mode as described in this study is critical in understanding the feasibility of using VPF for reverse thrust in future aircraft. The new capability to study the transition in a fully transient simulation can be used as a design development aid to define design and control characteristics of the reverse thrust VPF.

Keywords: variable pitch fan, forward-to-reverse thrust transition, feasibility study, dynamic flow field development

NOMENCLATURE

Roman characters

C	Rate of diffusion, constant
$\dot{m}$	Mass flow rate
N	Rotational speed
P	Total pressure
PAV	Average total pressure
$PAVLOW$	Depressed sector average total pressure
$PFAV$	Face average total pressure
T	Thrust

Greek characters

Γ	Stiffness factor
δ	Relative displacement
θ	Rotation angle
ζ	Stagger angle

Subscripts and superscripts

$disp$	Mesh displacement
i	Ring
j	Extent counter

[†]Joint first authors

ref	Reference value
<i>MTO</i>	Maximum take-off operating point
<i>n</i>	Intermediate fan blade aerofoil position
<i>stiff</i>	Mesh stiffness deformation coefficient
<i>z</i>	Axial direction component
<i>Abbreviations</i>	
ADP	Advanced Ducted Propulsor
GCI	Grid Convergence Index
ISA, SL	International Standard Atmosphere, Sea Level
OGV	Outlet Guide Vane
QCSEE	Quiet Clean Short-haul Experimental Engine
URANS	Unsteady Reynolds-averaged Navier-Stokes
VPF	Variable Pitch Fan

1. INTRODUCTION

Variable pitch fans (VPF) are an attractive design option for future civil gas turbine engines with high bypass ratios in the range of 12 - 15. This is because the use of VPF can extend the stable operating range of low-pressure ratio fan rotors that are required from engine performance requirements for such high bypass ratios. Previous studies have noted that the VPF in which the stagger angle of the fan rotor blades can be varied is a better option to manage the off-design fan operation and yield better fuel burn benefits than variable area nozzles that would become prohibitively heavy due to the large cold nozzle diameter in these high bypass ratio engines [1, 2]. Moreover, the VPF becomes an even more attractive option because it can be used to generate reverse thrust and eliminate the bulky conventional thrust reverser system resulting in significant aircraft level weight savings. The removal of the conventional thrust reverser also frees up the nacelle design constraints associated with accommodating the thrust reverser cascades and can accelerate the implementation of low installation drag ‘slim-line’ nacelles, leading to further fuel burn benefits [3, 4]. Therefore, a reverse thrust capable VPF can indeed provide a cascade of benefits that can significantly contribute to sustainable aviation and meeting aviation climate neutrality goals [5].

Reversal of airflow through the VPF can be achieved by rotating the fan blade aerofoils by around 90 degrees through either feather or flat pitch. Feather pitch refers to a feathered position, as in propellers where the aerofoils are aligned to the flow with minimal blockage, and flat pitch refers to the aerofoil surfaces perpendicularly blocking airflow with maximal blockage. Typically, the through feather pitch rotation that places no restriction on the blade pitch-chord ratio to avoid adjacent blade entanglement is preferred to the through flat pitch rotation. The aerofoil in reverse pitch mode results in a shift of the cascade throat area to the rear of the cascade row and causes the flow into the aerofoil passage to enter through the nominal outlet (see Appendix A).

NASA has explored the reverse thrust VPF in the Quiet Clean Short-haul Experimental Engine (QCSEE) and the Advanced Ducted Propulsor (ADP) programs. In brief, these programs were exploratory turbomachinery development programs that focused on developing reverse flow capable VPF designs among other objectives related to quiet and efficient propulsion systems. These programs established the feasibility of these designs and experimentally characterised the reverse flow VPF behaviour in

static isolated rigs and limited forward flow conditions [6–10]. The detailed fan design characteristics of a more representative, modern design practice ADP VPF in reverse thrust mode was described in a recent computational study [11]. Subsequently, the feasibility of utilizing a VPF for reverse thrust applications in realistic installed dynamic conditions in a future high bypass ratio engine in a typical aircraft has been studied by the authors using an integrated airframe-engine-VPF model. The details of the installed VPF flow field in reverse thrust mode, the distortion into the core engine during reverse thrust operation, the estimate of the airframe decelerating forces achievable with the reverse thrust VPF and a design improvement for augmenting the reverse thrust levels were described for a range of aircraft landing speeds and different VPF operational settings in a series of recent publications [12–15].

All these studies have been carried out by considering that the VPF is in reverse thrust mode after the aircraft touches down on the runway. However, before the VPF can get to the reverse thrust mode, it needs to transition from the nominal forward flow operating condition, at which the aircraft descends and touches down on the runway. Such information on the evolution of the flow field features through the VPF and the engine ‘during’ the transition of the VPF from nominal forward operating conditions to the reverse thrust mode after the aircraft touches down and as it rolls down on the runway is one of the key explorations that is required to enable the successful engineering of the reverse thrust capable VPF. Moreover, the insights obtained from such a transient flow field evolution study are necessary to understand the range of fan and engine operating conditions as well as the decelerating force on the aircraft that will occur during the transition. While in the isolated static rigs and outdoor modified engine rig tests in the QCSEE and the ADP program, the experiments included the transition from nominal operation mode to reverse thrust mode, no information on the flow field evolution through either the engine or the fan, even in the isolated static conditions, could be obtained due to a lack of extensive instrumentation.

Therefore, this time-varying flow field evolution during the transition into reverse thrust mode is described in this work. A novel implementation of a computational capability that models the motion of the rotor blade aerofoils as the VPF transitions to reverse thrust mode is used to capture the transience associated with both blade transition and gas dynamics. Additionally, the importance of using a ‘real time’ modelling method with blade motion as compared to the typical steady-state flow fields at discrete fan aerofoil settings is highlighted. The hitherto undescribed details of the flow field during transition as attempted in this study provide insights into the flow dynamics during the VPF transition to reverse thrust mode on aircraft and engine level parameters to ascertain the feasibility of using reverse thrust VPF in future aircraft.

2. INTEGRATED AIRFRAME-ENGINE-VPF MODEL

An integrated airframe-engine-VPF model with the VPF transitioning from forward to reverse pitch in a modern 40000 lbf two-spool geared turbofan engine with a bypass ratio of 14 is used to generate the dynamic flow field just after aircraft touchdown. The engine internal flow path consists of a VPF with 18

aerofoils, a core engine splitter with a portion of the entry duct into the engine core, an outlet guide vane (OGV) with 40 blade aerofoils, a complete bypass duct, a core exhaust duct, an aft-body casing and a plug. All components are represented by full annular geometries to capture the non-uniformities in flow development. The VPF blade design is developed with the same flow coefficient-stage loading distribution as in the reverse flow-capable NASA ADP rig with a forward flow design pressure ratio of 1.27, tip speed of 245 m/s, inlet diameter of 110 in. and a modified typical modern fan hub-to-tip ratio of 0.3. The VPF blade aerofoils are rotated by ζ_1° deg through feather pitch to reach reverse thrust mode. ζ_1° is a typical reverse flow stagger angle setting, within $\pm 10^\circ$ from the 90° stagger angle setting, that is characterized for reverse flow operation in previous studies. The VPF geometry as it transitions from a typical forward flow setting of 0° to ζ_1° is shown in Fig. 1. The other turbomachinery and internal flow path elements are sized using an in-house design tool, ATLAS, to match the engine performance requirements for the 40000 lbf engine and are representative of conventional engine design practice. The engine is wrapped in a short cowl axisymmetric nacelle, and it is connected to the airframe via a bespoke NACA aerofoil based pylon design. A typical airframe that houses two 40000 lbf engines is scaled from a baseline DLR F11 airframe with wing flaps and slats set in aircraft landing configuration. Inboard and outboard spoilers deployed in a conventional landing setting are also added to the wing model. A symmetric half of the airframe with the engine is placed in a large cuboidal far field domain that is bounded with a base edge to represent the rolling runway during the aircraft landing run. The integrated airframe-engine-VPF model is shown in Fig. 2. Except for the novel implementation of the moving walls in the VPF to study the transition to reverse thrust, all other components of the model are the same as in the studies conducted by the authors to explore VPF reverse thrust behaviour and further details about the complete model development can be found in [12]. The airframe-engine model does not include any reverse thrust VPF specific design modifications and is representative of the reverse thrust VPF placed in a typical conventional airframe-engine design.

3. COMPUTATIONAL MODEL SETUP

The models are discretized using a hybrid approach where an unstructured mesh is generated for airframe regions that are external to the engine and the bypass duct while structured grids are utilized for the rest of the internal engine flow path components. Unstructured grids are considered for regions where the flow direction is not known a priori, as in the passage-bound block, and structured grids for turbomachinery components. Grids of varying resolution were examined to establish grid independence and optimize the computational setup parameters. A total mesh size of ~ 50 million elements is finalized for the model with a representative Grid Convergence Index computed using the Richardson Extrapolation method of not more than 0.05 for key local and global parameters of interest. The dynamic flow field during transition is computed by means of a compressible, fully transient 3D URANS, coupled element-based finite volume solver, ANSYS-CFX, with imposed wall motion in the VPF blade row. The discretized equations are solved in a fully implicit manner with a

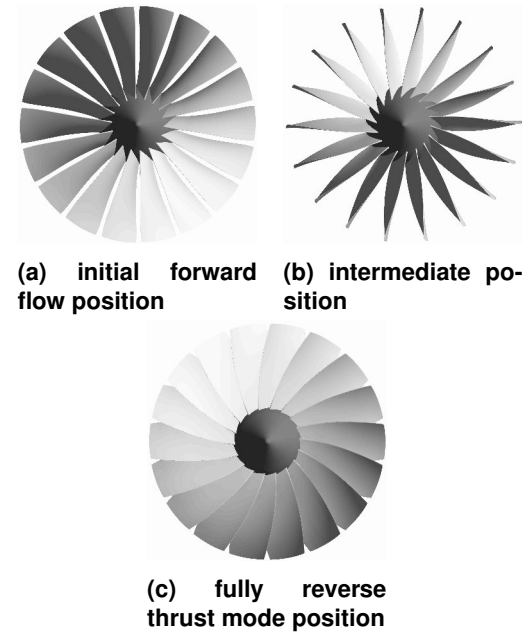


FIGURE 1: VPF BLADE AEROFOILS AT 3 DIFFERENT POSITIONS DURING TRANSITION FROM FORWARD OPERATING CONDITION TO THE REVERSE THRUST MODE

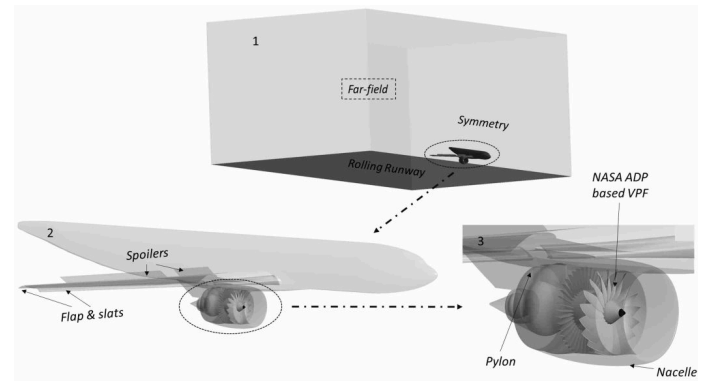


FIGURE 2: SCHEMATIC OF THE INTEGRATED AIRFRAME-ENGINE-VPF COMPUTATIONAL MODEL [12]

bounded second-order-accurate scheme for the spatial discretization and temporal integration is conducted using a second-order backward Euler scheme. The $k - \omega$ shear stress transport (SST) model is used to resolve the effects of turbulence. Automatic wall functions are not specified as near-wall flow physics are resolved with explicit grid refinement at all wall surfaces that are specified as adiabatic no-slip walls. A rigorous unsteady timestep choice study is conducted to ensure adequate resolution of the temporal flow field evolution and ensure stable, robust solver numerics with the imposition of gradual, small-step fan aerofoil wall motion to mimic the transition to reverse thrust. It is found that a temporal discretization that uses ~ 100 timesteps to capture 1 complete fan rotation satisfies all the flow-driven physical and solver imposed numerical requirements. This corresponds to a gradual 0.1° VPF aerofoil rotation in each timestep to achieve a near ‘real-time’ simulation of the complete transition. The description of this

aerofoil rotation is discussed in the next section. The chosen timestep respects physical advection timescales in the shortest flow transit domain within the fan passages and ensures several flow passes in the external far field domain as well. It was found that 10 inner coefficient loops are sufficient to achieve convergence for each timestep, and the numerical discretized equation residuals are reduced by at least three orders of magnitude in addition to a parametric variation of less than 0.5% before the solution advances in time. General grid interfaces that preserve fluxes are specified between domains with no relative motion. Flux and circumferential variation preserving, unsteady frozen rotor frame model is specified between the rotating fan aerofoil domain and the stationary domains of the OGV and the nacelle intake region. A comparative study with the detailed sliding rotor interface that discretely mimics fan rotation indicated variations of less than 2% in local fluxes and global parameters of interest. Therefore, the unsteady frozen rotor model with a specified rotating frame domain is considered appropriate to study the transition at a cheaper computational cost while retaining all the elements of relevant flow physics, as is common in turbomachinery practice.

The transition to reverse thrust will occur when the aircraft touches down on the runway. Therefore, since the aircraft is at the end of the descent phase and beginning of the landing run as the VPF will be engaged to transition to reverse thrust mode, the engine power is set in 'Approach Idle' conditions, which typically corresponds to a low fan rotational speed, N_1 , of 40% fan design speed. A typical touchdown velocity of 140 knots is specified for the moving ground wall that represents the rolling runway and for the freestream velocity in the far field domain. The far field is specified to be at ISA, SL conditions with 1 [atm] reference pressure and 288.15 [K] reference temperature. An engine thermodynamic performance model, built using the Numerical Propulsion System Simulation (NPSS) framework [16], is used to compute and specify the boundary conditions corresponding to approach idle at the core entry duct and the core exhaust nozzle. This ensures that the behaviour of the core engine is thermodynamically modelled and matched with the explicitly resolved regions in the integrated model. An axial velocity boundary condition that corresponds to a mass flow distribution is used at the core engine inlet. This ascertains that the pressure and temperature profiles into the core engine are computed to provide information regarding the core engine's operability. Total temperature and axial velocity are specified at the core exhaust nozzle inlet. This results in the establishment of an appropriate core exhaust jet in the engine exit regions to study the possibility of hot ingestion and resolve the resultant forces. The core engine is considered to operate at the same power level during the entire transition, as the VPF is also held at the same rotational speed.

The full transition to reverse thrust is estimated to last 1.5 seconds based on typical propeller pitch-change mechanism capabilities and the time required for full deployment of the conventional cascade thrust reverser systems. During the time required for transition, considering conventional decelerating forces on the airframe and solving a free-body problem, it is estimated that the aircraft slows down by approximately 3 knots. Since an aircraft speed change of this low magnitude is known not to significantly impact the flow physics from previous explorations in reverse

thrust mode, it is decided to keep the freestream velocity constant during the complete transition. Subsequent explorations are carried out for two other touchdown velocities, 160 and 120 knots, which represent typical velocity bounds. To understand the effect of touchdown velocities in this exploration, all other engine operating conditions are considered to remain the same. An additional study is also done to understand the effect of different fan rotational speeds at touchdown by considering an interval from the lower approach idle value of 40% up to a maximum of 80% fan design speed in steps of 10% with the 50% operating condition being excluded as it produces similar flow behaviour as the 40% one. It is very unlikely that the fan speeds will be significantly higher than the approach idle values, and this study is done only to understand the impact that the fan rotational speed has on the transition flow physics. In this study, the core engine boundary conditions are updated from the NPSS engine performance model corresponding to the fan rotational speed, while all other boundary conditions remain the same.

4. FAN AEROFOIL ROTATION

The transition to reverse thrust mode involves the rotation of the VPF aerofoils from a chosen nominal forward flow setting to the reverse flow setting of ζ_1° through feather pitch. To study the transition at typical 'Approach Idle' engine conditions, a forward flow setting of 0° is chosen. The 0° reference is considered for the baseline unrotated aerofoil configuration in forward flow operating mode. It is to be noted that 0° may not refer to the typical fan stagger setting at design point or take-off, since an additional degree of freedom to 'close' the aerofoils could be used for optimizing fan operability at different parts of the mission profile. Similarly, ζ_1° at reverse flow setting is chosen to be the typical upper bound rotated value and other reverse flow settings would need to be traversed to reach ζ_1° . Since the time required to rotate the VPF aerofoils to the reverse thrust position is several orders of magnitude higher than reverse flow development dynamic timescales, it is deemed necessary to resolve the dynamic wall motion to capture the transition flow dynamics. The ability to provide insight into this hitherto undescribed transition regime is important to quantify the flow mechanisms involved in the transition to reverse thrust rather than just the reverse thrust mode as in the previous studies.

The capability to rotate the fan blade aerofoils dynamically and physically as they transition from 0° to ζ_1° is developed by a novel implementation of imposed wall motion to investigate the time-varying transitional flow field. A wall motion transfer function with a local coordinate system for each of the 18 fan blade aerofoils is specified to simulate the rotating aerofoils. The wall motion is specified by an Eulerian rotation matrix using the equation below to compute the updated aerofoil locations after each timestep which corresponds to 0.1° rotation.

$$\begin{pmatrix} x_n \\ y_n \\ z_n \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_{n-1} \\ y_{n-1} \\ z_{n-1} \end{pmatrix} \quad (1)$$

where n is an intermediate step and θ the rotation angle of each step. The new location of the fan blade aerofoil is directly transferred to the wall boundary mesh elements of the discretized

geometry. The motion of the remaining nodes corresponding to the movement of the wall boundary mesh elements is computed by a solving a displacement diffusion equation shown below.

$$\nabla \cdot (\Gamma_{disp} \nabla \delta) = 0 \quad (2)$$

$$\Gamma_{disp} = \left(\frac{V_{ref}}{\Psi} \right)^{C_{stiff}} \quad (3)$$

where Γ_{disp} is a stiffness bunch factor that defines how different zones of mesh move. The mesh node motion is in such a way that nodes nearest to the wall absorb the wall motion completely, and the node motion to the internal nodes is diffused gradually depending upon C_{stiff} , which is a constant to control the rate of diffusion away from the wall. A value of 2.85 is found by trial to retain mesh quality throughout the transition; δ is the relative displacement with respect to the previous mesh location; Ψ is the control volume size; The displacement diffusion equation smooths nodes after mesh movement by specifying central, blended, or positive definite value-based diffusion parameters for interior and boundary elements. The net effect of the displacement diffusion due to wall movement and the zonal motion is pictorially described in Fig. 3 for clarity.

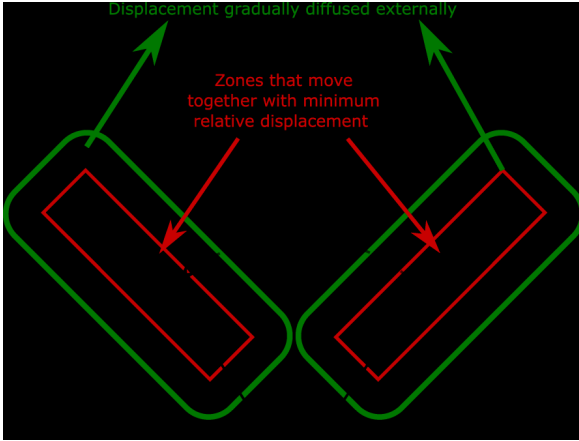


FIGURE 3: SCHEMATIC REPRESENTATION OF DISPLACEMENT DIFFUSION AND ZONAL MOTION DURING FAN BLADE AEROFOIL TRANSITION

Mesh folding is avoided by gradual small step deformation that is only 0.1° for each unsteady timestep. Additionally, different areas of the grid topology are bunched into zones with specifications of variable stiffness in the displacement diffusion equation with special treatments for the leading and trailing edge regions. Numerically, since the displacement step is computed with reference to the previous mesh location and the step size is small, sharp changes to the nodes are avoided. No constraints are specified in the blade passage boundaries with motion from the wall nodes being diffused gradually even to the interfaces between the blades. Since such identical equations are solved for adjacent blades, a ‘free’ displacement makes the solution of the displacement equations robust [17].

Moreover, a novel mesh probe-and-update routine is implemented during which the mesh quality is probed at each timestep by examining a mesh determinant value that is representative of

mesh element skewness angles and volumes. At any timestep, when the pre-defined determinant value that is representative of typical turbomachinery meshing practice guidelines is violated, a new mesh for the geometry is re-created in an automated external re-meshing routine. Since the re-created mesh is in the same topology as the baseline mesh and has similar elemental distributions, a one-to-one zonal match ensures the transfer of all solution vector space parameters to proceed with the time-marching. Several trials are conducted to identify timesteps at which the mesh thresholds are violated. It was identified that an aggressive grid quality threshold can be maintained throughout the transition if the meshes are updated every 5° . The mesh update routine is automated using a script to ensure a similar grid topology and a 100% zonal match from the previous timestep for flux interpolation on the updated mesh at the subsequent timestep. In this way, the mesh elements are always ensured to have element skewness angles between 30° to 150° , and minimum elemental volume at least 30% above a notional null volume element around a node. The preservation of grid quality for different timesteps is illustrated by the meshes shown in Fig. 4.

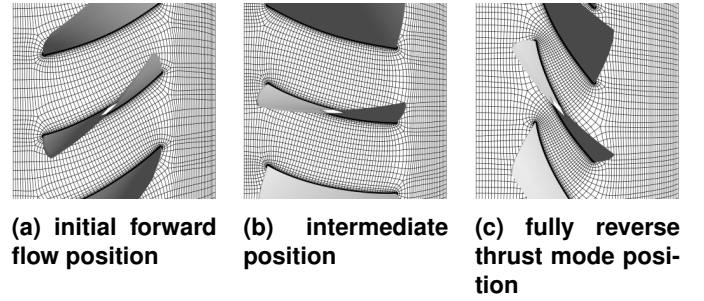


FIGURE 4: GRID EVOLUTION DEPICTED AT THREE STAGGER ANGLES DURING VPF TRANSITION

The solutions are carried out in a High Performance Computing (HPC) facility, ‘DELTA’, with 192 cores, 1888 GB of shared RAM and 60 Teraflops of peak processing speed using a Message Passing Interface (MPI) parallelization scheme. Optimized recursive bisection for large problems is chosen for partitioning. Memory overrides up to 2x the typical values are found to be required for preconditioning the solution. In this facility, each timestep of about 1 millisecond in physical time is solved in 15 to 20 minutes of real time. The complete transition to reverse thrust can be simulated in a relatively modest timeframe of 5 to 7 days, making the method capable of handling detailed pre-design exploration studies. Key challenges regarding export of solution data at each timestep is solved by using automated file transfer scripts and it was found that drive memory management posed a greater challenge than the computational requirements. Additionally, the flow field evolution results from the detailed transition studies as described in this section are compared with quotidian 3D RANS solutions for 10 discrete rotated aerofoil locations between nominal and reverse thrust modes. These 3D RANS solutions typically require around 10 hours of computational time for each angle setting to converge in the same HPC facility. The comparison is done to illustrate the differences that can be captured by imposing wall motion dynamics in addition

to flow dynamics at each timestep.

5. RESULTS AND DISCUSSION

To describe the complete forward-to-reverse thrust transition operation, the results are presented and discussed in the following order:

1. The transient flow field evolution during the transition to reverse thrust mode is described at the typical 'Approach Idle' fan power setting with 40% N_1 and a typical aircraft touchdown speed of 140 knots. In this section, initially the general flow field in the nominal forward flow condition is briefly described, even though it is typically well understood, as this represents the starting point of the transition to reverse thrust. Thereafter, the dynamic flow field evolution that includes the initial development and evolution of the reverse flow within the engine internal flow path, a detailed description of the fan flow field characteristics during the transition and its corresponding impact on the airframe regions outside the engine are discussed. The flow distortion at the core engine entry is quantified to provide insights into the engine's operability. Additionally, the dynamic evolution of the resultant axial decelerating force levels during the transition is also computed.
2. The effect of fan rotational speed on the dynamic flow development during the transition is described at the constant typical aircraft touchdown velocity of 140 knots. The selected fan rotational speeds range from 40% to 80% of the fan design speed. It is emphasized that the landing fan rotational speed and power setting are unlikely to be higher than the 'Approach Idle' 40% speed condition, and it is in the vicinity of this speed that the transition to reverse thrust will most likely occur. This numerical exploration is intended to understand the flow physics change of the transition at notional higher rotational speeds.
3. The effect of aircraft landing speed on the transition flow physics is described at a constant typical 'Approach Idle' fan power setting of 40% N_1 . Two additional aircraft landing speeds, 120 knots and 160 knots, that represent the most likely minimum and maximum touchdown velocities are considered.
4. A comparison between the fully transient transition flow field solution with wall dynamics and typical 3D RANS solutions at discrete fan blade aerofoil settings along the transition to the reverse thrust mode stagger angle setting is described.

5.1 Transition Flow Field at 40% N_1 and 140 knots Aircraft Touchdown Velocity

5.1.1 Nominal Flow Field at Forward Flow Setting.

The general forward flow field within the engine as well as externally at this typical representative transition condition is shown in Fig. 5 using 2D streamlines projected on a mid-engine surface that extends out into the airframe regions and 3D streamlines that indicate the overall engine flow and the core flow streamlines

separately. The streamlines coloured by axial velocity indicate the typical expected flow field when the VPF is at full forward flow position. The flow entering the engine is nearly uniform and is accelerated as it leaves the bypass and the core duct. Externally, the streamlines divide around the nacelle and in the nacelle-ground gap, the acceleration due to the ground effect is captured. In the 'Approach Idle' engine power setting, the mass flow ingested by the core is only 54% of the maximum take-off condition value, which results in lower values of axial velocity in the fan's inner annular regions and at the core entry. Fig. 6 shows the total pressure contours at 5 streamwise planes along the engine length corresponding to the bypass exit, OGV outlet, core inlet, fan outlet and fan inlet. A typical circumferentially uniform flow field with higher work addition in the fan outer annular regions and minimal distortion in the core engine entry plane is observed as expected. These contours and streamlines indicate the typical flow field within and around the engine as the aircraft touches down on the runway at which juncture the thrust reverser would be engaged and the transition of the VPF aerofoils to reverse thrust setting would begin. The dynamic development of this flow field during the time it takes to transition to full reverse thrust is discussed by describing the flow field changes in these contours and streamlines.

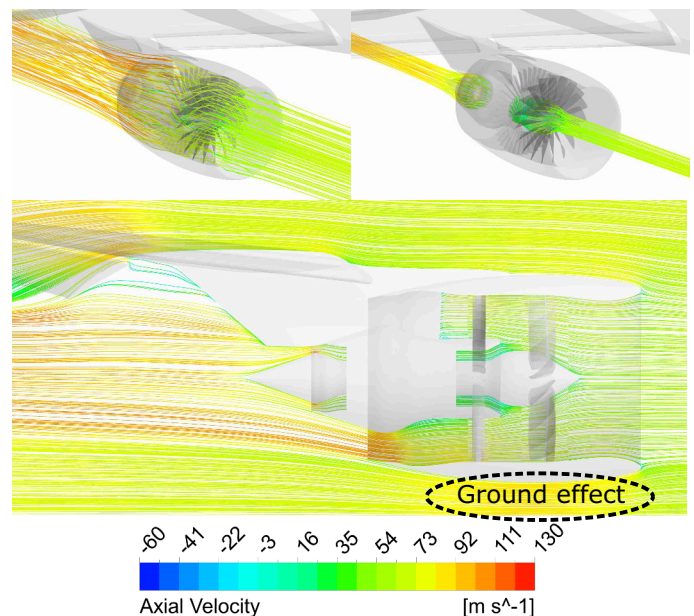


FIGURE 5: INTERNAL AND EXTERNAL TO THE ENGINE FLOW FIELD AT NOMINAL FORWARD FLOW OPERATING CONDITION HIGHLIGHTED BY 2D AND 3D STREAMLINES COLOURED BY AXIAL VELOCITY

5.1.2 Flow Field Evolution during Forward-to-Reverse Thrust Transition.

The detailed flow field vector solution space is recorded for each 0.1° during the fan aerofoil rotation from the forward to reverse thrust stagger angle setting. This provides a near 'real-time' peek into the dynamic development of flow features within the engine and the external airframe regions. After the completion of the transition to reverse thrust mode in 1.5 seconds, the flow is allowed to develop for another second at the

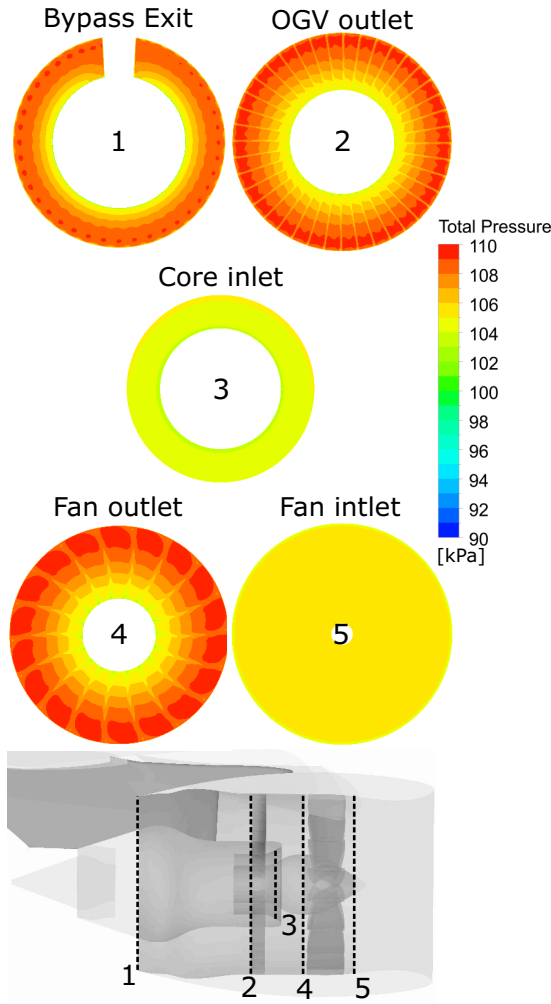


FIGURE 6: TOTAL PRESSURE CONTOURS AT DIFFERENT LOCATIONS IN THE INTERNAL ENGINE FLOW PATH. CORE INLET PLANE IS SCALED FOR A MORE DETAILED VIEW

reverse thrust setting. A 0.125 second delay due to gas dynamic effects is noticed before the flow field evolution settles into full reverse thrust mode. The trends in the mass flow rate ingested by the engine, as shown in Fig. 7, are used to downselect the flow field at three key timestamps corresponding to stagger angles on the way to transition. In the first 15 degrees of fan aerofoil rotation, a minor increase in the flow ingested by the fan is observed. The increase happens because this initial opening of the fan aerofoils increases the throat area, and the incidence change is not high enough to cause the flow within the fan passages to separate. Thereafter, the mass flow decreases continuously because the flow within the fan passages separates, which in turn triggers flow field changes within the engine. Therefore, three timesteps for three different stagger angles, 42° , 58° and ζ_1° , which correspond to the appearance of key flow field features, are chosen for the purposes of discussion and illustration. These flow field features are highlighted in the same mid-engine surface plane streamlines and contours at the 5 streamwise planes as in the nominal flow field.

Figs. 8 to 11 show various aspects of the flow field evolution

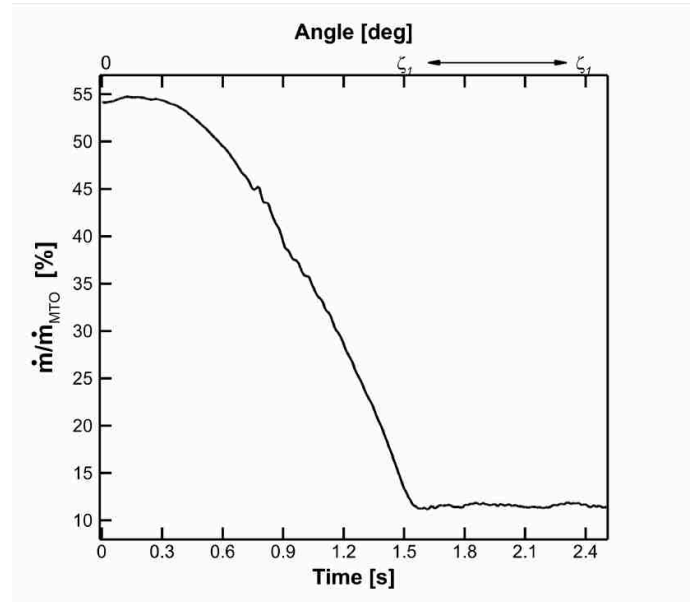


FIGURE 7: PERCENTAGE OF MASS FLOW RATE EVOLUTION INGESTED BY THE ENGINE AND NORMALIZED BY THE CORRESPONDING MAXIMUM TAKE-OFF VALUE DURING VPF TRANSITION

that are used to describe the evolution of flow features during the fan transition. The streamlines on the mid-engine surface that extend out into the airframe for the three timestamp stagger angle settings are shown in Fig. 8. The corresponding contours of axial velocity and total pressure in the 5 streamwise planes along the engine are shown in Figs. 9 and 10. The Mach number contours overlaid with the streamlines for the timestamps at different spanwise locations along the fan aerofoil passages are shown in Fig. 11. In the axial velocity contours, positive values indicate nominal forward flow and negative values indicate reverse flow.

At 42 degrees, the fan aerofoil sections in the tip regions have reached the feathered configuration. Consequent to this, the trailing edge portion of the fan blade aerofoils in locations beyond 50% span stalls and the resultant flow separation is noticed in the fan outlet. This stalling results in a drop in the mass flow ingested by the engine. The development of this lower mass flow within the bypass duct causes the appearance of a recirculation region in the hub of the bypass duct, immediately after the OGV blade row, due to the radially outward shift of the flow from fan aerofoil passages. The radial outward shift of the fan streamlines occurs because, as the fan blade reaches 42 degrees, the fan tip sections are more open than the hub sections due to the baseline throat area and twist angle variation. This recirculation region is the incipient beginning of the development of the reverse stream, which further continues to grow as the fan transitions.

At 58 degrees, the recirculation region has grown and occupies a significant portion of the bypass duct. Two factors contribute to this: 1) The continuing decrease in the fan mass flow with the increase in the separated flow regions occupying the fan aerofoil passages. 2) The lower spanwise portions of the fan have had a shift in the cascade throat area towards the rear of the aerofoil in that it is already in reverse flow mode. Therefore, the fan

suction has begun to act in the nominal fan outlet and the bypass regions. This action of the fan suction in the inner annular regions is sufficient to pull a portion of the flow in the bypass duct and set up a ‘reverse stream’ that is just strong enough to pass through the OGV blade row. This backflow then feeds the core engine by turning 180 degrees at the splitter and disrupts the flow splitting between the core and the bypass duct. The reverse stream forms a shear layer with the freestream ingested from the fan (highlighted by a black solid line arrow), which is in turn pushed radially outwards and restricted in the outer annular regions of the bypass duct with high axial velocities due to stream tube contraction. At this stage, there is a significantly lower amount of flow exiting the bypass duct as compared to the nominal operation because of both the reduction in flow ingestion and the pull exerted on the ingested flow that sets up the reverse stream. On the other hand, throughout the transition, the core engine flow remains constant to power the fan at the same rotational speed.

As the fan continues rotating and reaches the reverse thrust mode at ζ_1° degrees, the reverse stream continues to grow because of the fan suction acting in the nominal outlet regions while the mass flow ingested into the engine drops significantly. The flow field when the fan is at the fully reverse thrust position has three main features as marked in Fig. 8:

1. The freestream enters the fan rotor and is centrifuged outwards within the fan passages by the fan rotation and the reverse stream. Both streams meet in a shear layer and move radially outward towards the fan casing.
2. The reverse stream splits into two streams near the splitter at the core inlet. One feeds the core stream with the 180° turn, which results in a separation zone in the outer annular regions close to the splitter edge. The remaining portion of the reverse stream enters the fan passages where it meets the freestream in the shear layer.
3. The mass flow ingested into the engine has dropped significantly from 54% of the corresponding maximum take-off value at the start of the transition to around 10% at full reverse thrust mode. Correspondingly, a large drop in the axial velocity at the intake because of the fan suction shifting to the rear is noticed. This reduction in mass flow leads to topological changes in the stream tube captured into the engine, as expected in low mass flow conditions. This results in a shift of the stagnation point at the nacelle lip that is due to the flow division into and outside the engine to move further into the intake.
4. Most notably, at this low ‘Approach Idle’ power setting, no reverse flow manages to escape out of the fan inlet and the nacelle intake. At this condition, the reverse flow due to the fan at reverse thrust setting effectively appears as a large blockage to the flow through the engine while sufficiently feeding the core engine to rotate the fan at constant speed.
5. This increase in blockage to flow through the engine causes the freestream air to spill around the engine. Throughout the transition, corresponding to the decrease in the mass flow drawn into the engine, there is an increase in the air spilled

around the engine, which appears in the changes notable at the nacelle intake lip in Fig. 8. As this spillage increases, the ground effect acceleration and the flow spread velocity around the engine increase too.

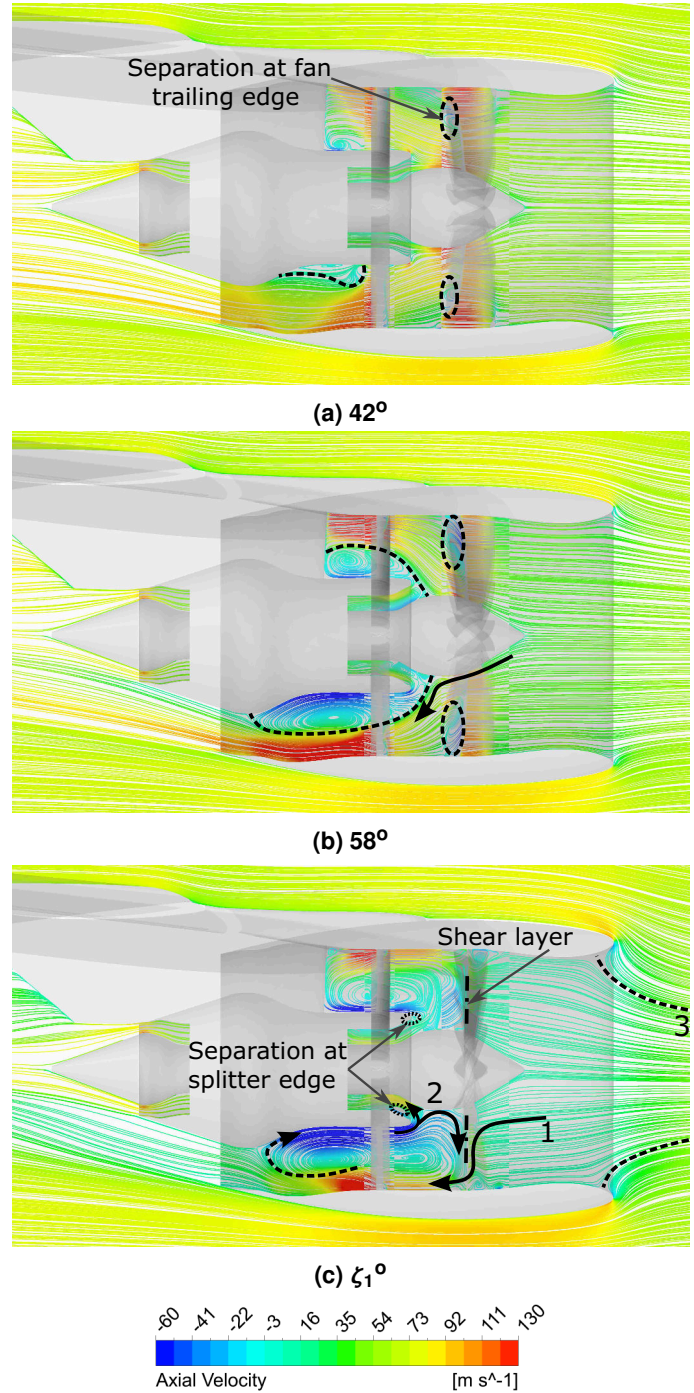


FIGURE 8: FLOW FIELD EVOLUTION INTERNAL AND EXTERNAL TO THE ENGINE REGIONS DURING VPF TRANSITION

The total pressure evolution during the transition is depicted at five different engine locations for the three timestamp stagger angles as well as for the nominal forward flow condition in Fig.

9a. As the fan rotor repitches, there is a decrease in total pressure within the engine because of the reverse stream development. As noted before, the reverse stream occupies regions close to the inner span of the bypass duct and grows in size as well as in momentum with the fan blade rotation. This recirculation zone is noticed to be asymmetrical and has circumferential variations in the total pressure and axial velocity contours due to the fan rotation with the stalled aerofoil passages. Eventually, the shear interaction of the reducing amounts of freestream with the increasing amount of reverse stream results in a total pressure drop as the transition proceeds. The core inlet plane is characterised by a decrease in total pressure throughout the operation and a significant drop is noticed when the core is fed by the reverse stream. At the fan outlet, the signature of the fan stall is visible at 42° and thereafter with the increase in pitch, the radially outward migration of the pressurized flow is visible at 58°. After this, the temporally strengthening reverse stream with the increase in fan suction results in the reverse stream entering the fan passages in the outlet, the signature of which is observed as a large low-pressure region. Near the outer annulus of the fan outlet, the pressurized turned back reverse stream and the freestream are observed. At each plane, the regions occupied by the reverse stream, its development and interaction with the freestream that result in the total pressure field evolution are seen in the axial velocity contours of Fig. 9b.

5.1.3 Fan Flow Field. The fan flow field evolution during the transition is described in detail in this section since it is the changes in the fan that drive the engine and the external airframe flow field. Fig. 10 shows the spanwise variation of axial velocity for the three timestamp stagger angle settings at the fan inlet and outlet with two extra angles added to show the evolution of axial velocity throughout the transition. Fig. 11 shows the streamlines overlaid on the Mach number contours at different spanwise locations. At the fan inlet, it is noticed that the axial velocity decreases as the fan transitions to reverse thrust mode. Initially, an increase in blockage due to the stalled passages and thereafter the shift in the fan suction to the rear of the aerofoil cascade causes a decrease in mass flow ingested into the engine, which appears as a drop in the axial velocity. As noticed in the trends of axial velocity at 42 degrees, the stalling of the fan blocks more of the tip passages and thereafter the stalled region increases in size and occupies the entire passage while the reverse stream develops from the rear of the cascade. Notably, as described earlier, at this low power ‘Approach Idle’ condition, no reverse flow manages to come out of the fan inlet even at the end of transition.

At the fan outlet for the stagger angle of 42 degrees, the signature of the fan tip stall is observed in the negative axial velocities and in the large separation zone in the streamline plot. This stalling results in a redistribution of the mass flow that appears as an increase in the axial velocity at regions near the hub. Further at 58 degrees, the stalled region increases across the span, as seen in the streamline plots, which results in a redistribution of the flow towards the radially outward regions, where there is an increase in the throat area as the passages open. At 75 degrees, the signature of the reverse stream appearance at the fan outlet is observed. This reverse stream further bolsters the radial outward

migration of the freestream. Finally, at the reverse thrust mode setting, a significant increase in the reverse stream is observed in the lower annular regions with increased negative axial velocities. Additionally, all the reverse stream and the centrifuged freestream exit into the engine in the nominal forward flow position in the top 40% span of the fan passages as indicated by the positive axial velocities.

The development of these fan flow features impacts the fan power absorption. The fan power evolution, as computed by the integral of the blade torque and angular velocity, is shown in Fig. 12 and is normalized by the nominal forward flow value. It is observed that fan power increases until it reaches a peak of 2x the nominal value at a 49 degree stagger angle and thereafter continues to decrease until it reaches the reverse flow stagger angle setting. The power at the final reverse flow setting is 1.5x the nominal value. Till 49 degrees, there is a 10% drop in the total mass flow ingested by the fan from the inlet. However, the progressive increase in the stalled passages throughout the fan aerofoil span causes a nearly 3x rise in the total enthalpy change and consequently the work coefficient. This in turn appears as an increase in total power transferred from the fan to the flow at the constant rotational speed setting. However, beyond 49 degrees there is a sharp decrease in the mass flow ingested by the fan because of the growing reverse stream in the engine exit regions. Therefore, even with an increased enthalpy rise and work coefficient, the total fan power transferred to the flow reduces as compared to the peak power. At the final reverse flow setting, the power transferred to the flow is still higher than the nominal operating condition because, even with the additional reverse stream flow, the total flow handled by the fan passages reduces because of the sharp drop in the freestream flow, which consequently increases the total enthalpy change and the work coefficient at constant fan rotational speed. This change in the power transferred from the fan to the flow has implications for the core engine’s operability and control in that if the fan were to be maintained at a constant rotational speed during transition, the power produced by the core engine would need to accommodate this increased demand. This would need to be translated as an increase in the fuel schedule while ensuring that the increased turbine entry temperatures are within specified limits.

5.1.4 Resultant Airframe Axial Decelerating Force. The resultant axial decelerating force on the airframe is computed by applying momentum conservation to a control volume that encapsulates all the fluid wetted body surfaces and extends into the far field domain. The resultant near field force term is computed as an integral of the pressure and shear stresses on all the fluid wetted surfaces:

$$F_z = \oint [-pn + \tau.n]dS \quad (4)$$

where F_z is the axial force with positive values indicating decelerating force acting along the fuselage axis of the airframe from the nose to the empennage, p is the pressure term, τ is the shear stress tensor, n is the unit normal vector to the elemental surface area and S indicates all the fluid wetted surfaces. The far field force term from the control volume faces is not included in the discussion here because it will include a time lag associated with

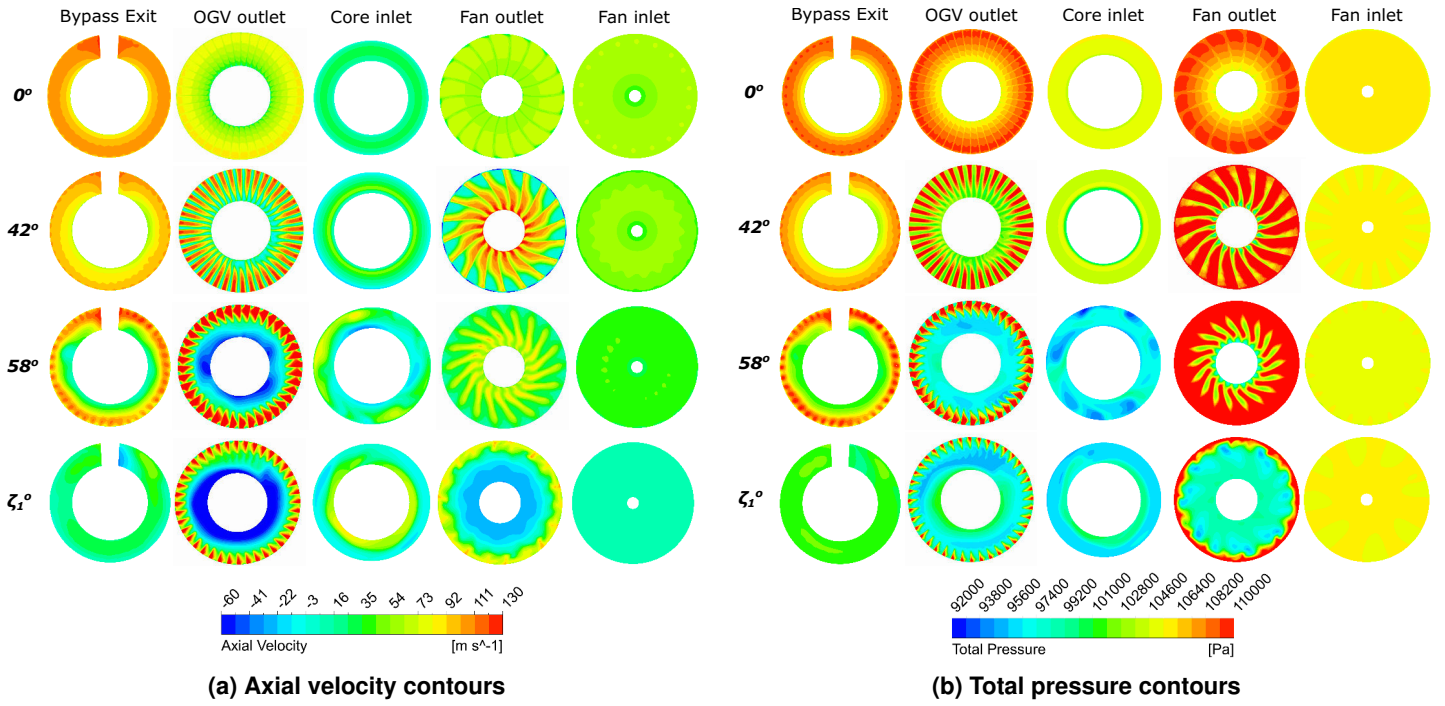


FIGURE 9: AXIAL VELOCITY AND TOTAL PRESSURE CONTOURS AT DIFFERENT LOCATION IN THE INTERNAL ENGINE FLOW PATH. CORE INLET PLANE IS SCALED FOR A MORE DETAILED VIEW

the convective timescales of the flow to reach the notional control volume faces. Further details of the resultant force estimation method are discussed in [15].

The evolution of this axial decelerating force during the transition to reverse thrust mode is shown in Fig. 13. Initially, in the nominal forward flow mode at the aircraft touchdown, there is no resultant decelerating force on the airframe since the engines produce thrust just to overcome the total aircraft drag. Thereafter, for the first 15 degrees of transition, there is an increase in the decelerating force due to increase in the mass flow ingested by the pre-stall, more open fan passages. After this, the decelerating force drops to zero before increasing to values up to 12% of T_{MTO} (maximum take-off thrust) near the middle of the transition. This is because there is a gas dynamic time delay between a reduction in the mass flow ingested by the fan and its effect being felt as a drop in the bypass duct thrust and an increased mass flow spilled around the intake. Thereafter, beyond the middle of the transition, once again a drop in the decelerating force is noticed before it reaches a value of 15% of maximum take-off thrust at the reverse thrust stagger angle setting. This is because of the time delay between the action of fan suction on the fan aerofoil cascade rear and its corresponding effect to occur in the intake and bypass exit flows. The decelerating force of 15% T_{MTO} is in the expected range for the ‘Approach Idle’ setting of 40% N_1 at an aircraft touchdown velocity of 140 knots because from previous explorations, it is known that at around 80% N_1 , the axial decelerating force is about 40% T_{MTO} .

5.1.5 Total Pressure Distortion Indices. The core engine operability during the transition is influenced by the transient evolution of the flow distortion at the core engine inlet. The flow

properties at the core engine inlet are analysed to compute the circumferential and radial total pressure distortion indices which are known to impact stable core engine operation. The circumferential distortion index (CDI) is computed by using the following method:

$$PAV_i = \frac{1}{360} \int_0^{360} P(\theta)_i d\theta \quad (5)$$

$$PAVLOW_i = \frac{1}{\theta_j} \int_0^{\theta_j} P(\theta)_i d\theta \quad (6)$$

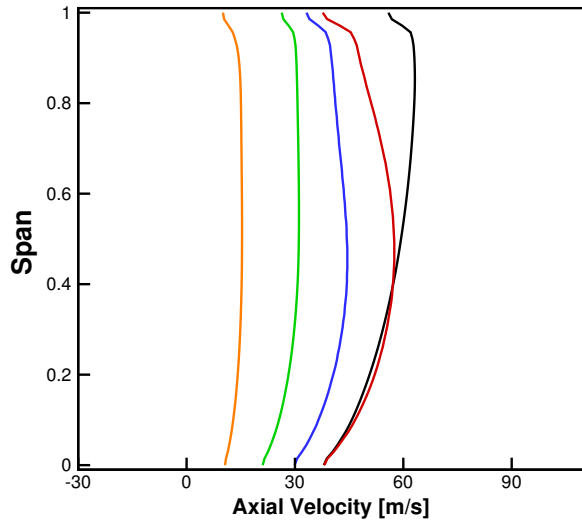
$$CDI_i = \frac{PAV_i - PAVLOW_i}{PAV_i} \quad (7)$$

where $P(\theta)_i$ is the total pressure distribution, PAV_i is the ring average total pressure and $PAVLOW_i$ is the total pressure average in the depressed extent that is below the average total pressure. The CDI is typically computed for 5 rings that divides the annulus into equal areas following SAE recommendations. The radial distortion index (RDI) is computed for the entire face by:

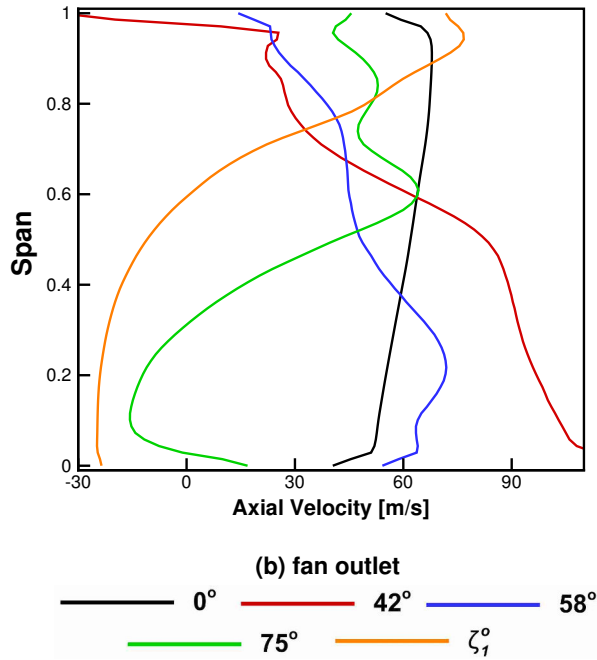
$$RDI_i = \frac{PFAV - PAV_{i,min}}{PFAV} \quad (8)$$

$PFAV$ represents the face average total pressure and $PAV_{i,min}$ is the minimum of individual ring average total pressures. Further details about the method used is described in [14].

The CDI and RDI values for the complete transition are shown in Fig. 14. In general, a typical threshold value of 0.07 is used as an indicator for distortions that will begin to impact the core engine’s stable operation [14]. The values of both the distortion indices are low and well within this notional threshold throughout the transition. A peak in the radial distortion index



(a) fan inlet



(b) fan outlet

FIGURE 10: SPANWISE VARIATION OF CIRCUMFERENTIALLY AVERAGED AXIAL VELOCITY AT FAN INLET AND OUTLET FOR FIVE STAGGER ANGLE SETTINGS DURING VPF TRANSITION

near the middle of the transition is observed. This corresponds to the switch-over when the core engine stream is fed by the reverse stream developing in the bypass duct rather than the freestream. An increasing trend in the CDI is observed after the middle of the transition because the reverse stream that feeds the core engine has circumferential non-uniformities due to fan rotation and a circumferential variation of the separated region in the bypass

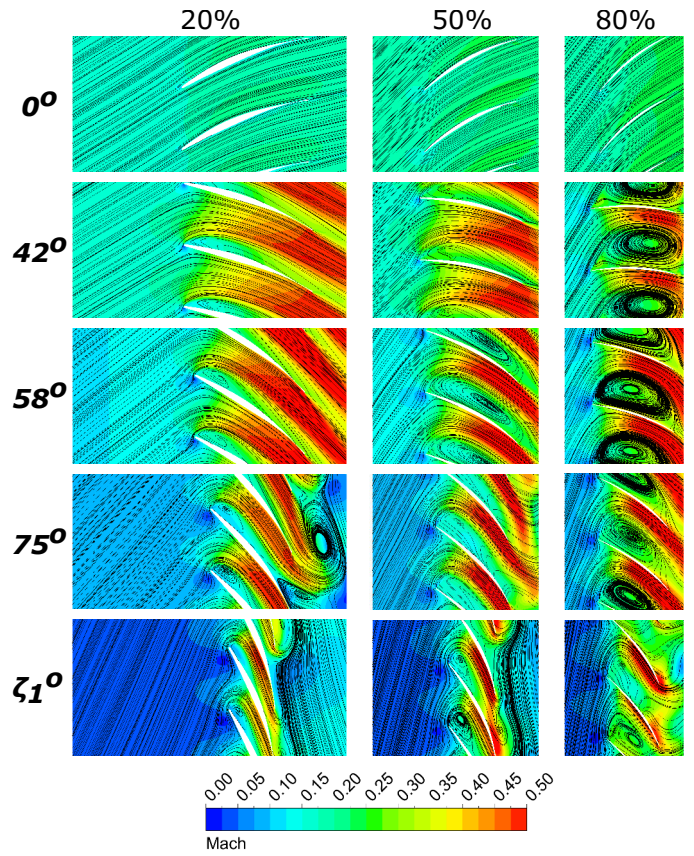


FIGURE 11: MACH NUMBER CONTOURS AT 20%, 50% AND 80% SPAN ALONG WITH TRANSIENT STREAMLINES SHOWING STALLING DEVELOPMENT PROCESS DURING VPF TRANSITION

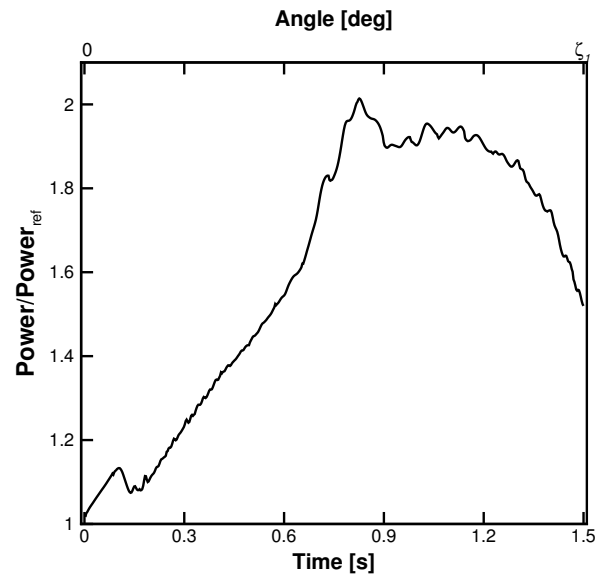


FIGURE 12: EVOLUTION OF FAN POWER ABSORPTION NORMALIZED BY THE NOMINAL FORWARD FLOW VALUE DURING VPF TRANSITION

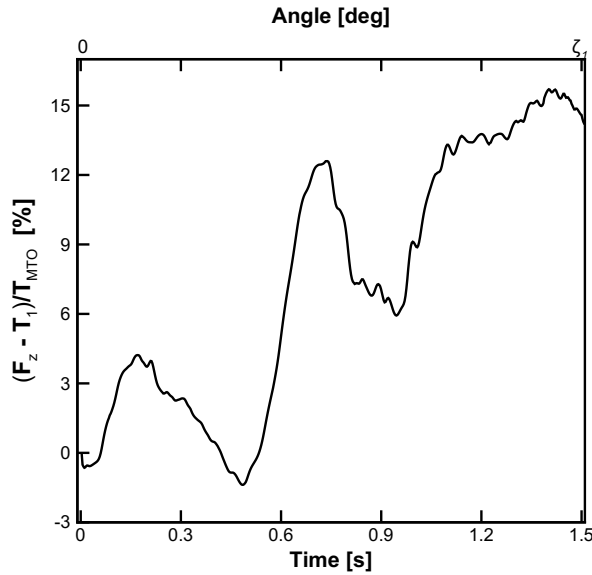


FIGURE 13: EVOLUTION OF PERCENTAGE OF AXIAL DECELERATING FORCE NORMALIZED BY THE MAXIMUM TAKE-OFF THRUST VALUE DURING VPF TRANSITION

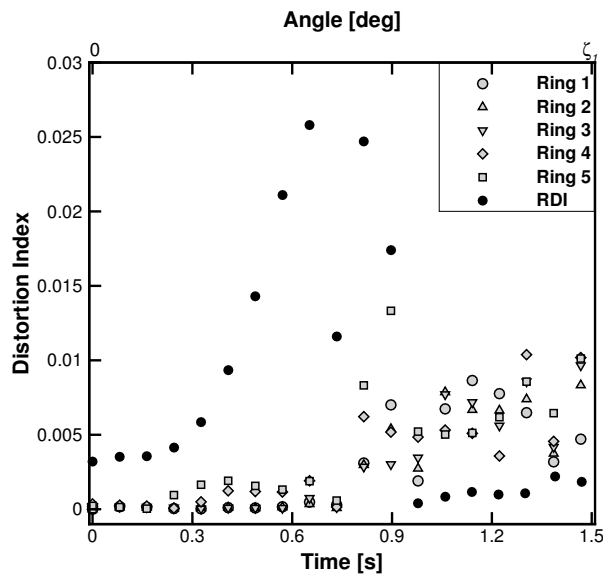


FIGURE 14: EVOLUTION OF CDI AND RDI DURING VPF TRANSITION

duct from which it emanates. These low values indicate that there are unlikely to be any issues related to core engine operability due to flow distortion at the core engine inlet.

5.2 Effect of Fan Rotational Speed on Transition

The effect of fan rotational speed on the dynamic flow field evolution during the transition to reverse thrust mode at a constant aircraft touchdown velocity of 140 knots is discussed in this section. In addition to the typical 40% rotational speed in the ‘Approach Idle’ power setting, three additional rotational speeds,

60%, 70% and 80% are chosen to understand this effect. The core engine operating conditions corresponding to the increase in fan rotational speed are worked out from the engine thermodynamic model in NPSS and updated in the computational model. It is emphasized that these higher rotational speeds are explored to numerically understand the flow field and it is unlikely that these speeds are used during aircraft descent. Rotational speeds below the ‘Approach Idle’ are also unlikely to occur at aircraft touchdown.

The evolution of the ingested mass flow for different fan rotational speeds during the transition is seen in Fig. 15. At the beginning of the transition, there is an increase in the nominal mass flow ingested into the engine with an increase in the fan rotational speed, as expected from the nominal fan characteristics. Near the middle of the transition, the mass flow ingested at all the rotational speeds converges because around this region near the feathered configuration, the stall in the fan flow passages occupies a significant portion of the fan aerofoil passages. Consequently, the blockages due to the stall extending through the fan blades are not significantly affected by relative changes in the fan axial velocity and the rotational speed, which results in similar mass flows being ingested. Beyond the feathered configuration, the increased fan rotational speeds produce higher suction in the rear of the fan aerofoil cascade. Consequently, a sharper decrease in the mass flow ingested through the engine is noted with increased rotational speeds. Finally, in the reverse thrust mode, the higher rotational speeds beyond 60% have reverse flow coming out of the fan and the nacelle inlet, while at 40% rotational speed there is no reverse flow out of the fan. Since it is only above 60% that a reverse flow is observed to flow out of the fan inlet, the rotational speeds below 60% are not shown in this discussion. At the 80% rotational speed, significant unsteadiness is observed due to the interaction of similar momentum reverse stream and freestream in the shear layer within the fan aerofoil passages. Therefore, at the end of the transition, the mass flow out of the fan at 80% is not significantly larger than the 70% rotational speed. However, if the flow at the reverse flow stagger angle setting is allowed to develop for another second, the higher suction with the higher rotational speed sets up a larger reverse flow.

The flow field when the VPF has reached the fully reverse thrust position at the 3 higher fan rotational speeds is shown in Fig. 16. Here, the fan suction to create the reverse flow is sufficient in all cases to push the reverse stream out of the intake and cause flow to be ingested by the bypass nozzle exit plane. The following changes are observed as the fan rotational speed increases:

1. The amount of reverse flow that comes out of the intake is increased. This affects the external flow field, especially close to the nacelle lip region, where the reverse stream that is turned back towards the engine exit by the freestream begins to lift off the nacelle. This is because the reverse stream momentum begins to increase and the freestream is no longer able to make it stick to the nacelle’s outer regions.
2. The amount of flow entering the engine at the bypass nozzle exit is increased as observed in the axial velocity values.

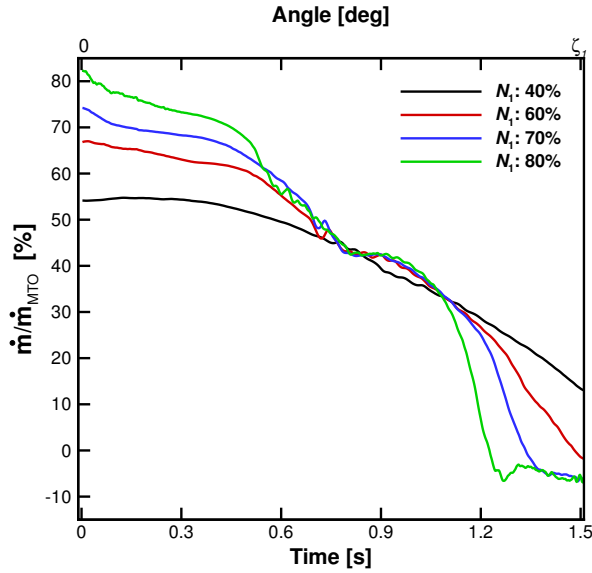


FIGURE 15: PERCENTAGE OF MASS FLOW RATE EVOLUTION NORMALIZED BY THE CORRESPONDING MAXIMUM TAKE-OFF VALUE AT DIFFERENT FAN ROTATIONAL SPEEDS DURING VPF TRANSITION

Corresponding to this the separation at the bypass nozzle lip decreases in size.

3. The amount and momentum of the reverse stream entering the fan aerofoil passages increase. This causes the shear layer where the reverse stream meets the freestream from the intake to be pushed towards the fan inlet. As both streams are centrifuged within the fan passages, the larger momentum of the reverse stream at the higher rotational speed causes more of it to escape while only smaller amounts are turned back into the engine at the fan outlet near the outer annular regions. The changes in the fan flow field are shown using meridional velocity vectors in Fig. 17.
4. The turned back stream from the fan passages towards the nominal engine outlet is washed down by the reverse stream developing from the bypass exit. The higher momentum of the reverse stream progressively causes a reduction in the space occupied by this turned back stream from the fan outlet.

The effect of the change in fan rotational speed on the evolution of the axial decelerating forces on the airframe is shown in Fig. 18. A larger amount of axial decelerating force is observed at higher rotational speeds. The general trend of the force evolution also remains at lower rotational speeds with similar time delay driven peaks and troughs at lower stagger angle settings. The relative dominance of the reverse stream momentum has resulted in a lower change in the decelerating force near the feathered configuration. The unsteadiness associated with the shear layer interaction of the reverse stream and the freestream in the fan aerofoil passages causes a minor drop and increase in the decelerating force while the reverse stream develops near the full reverse

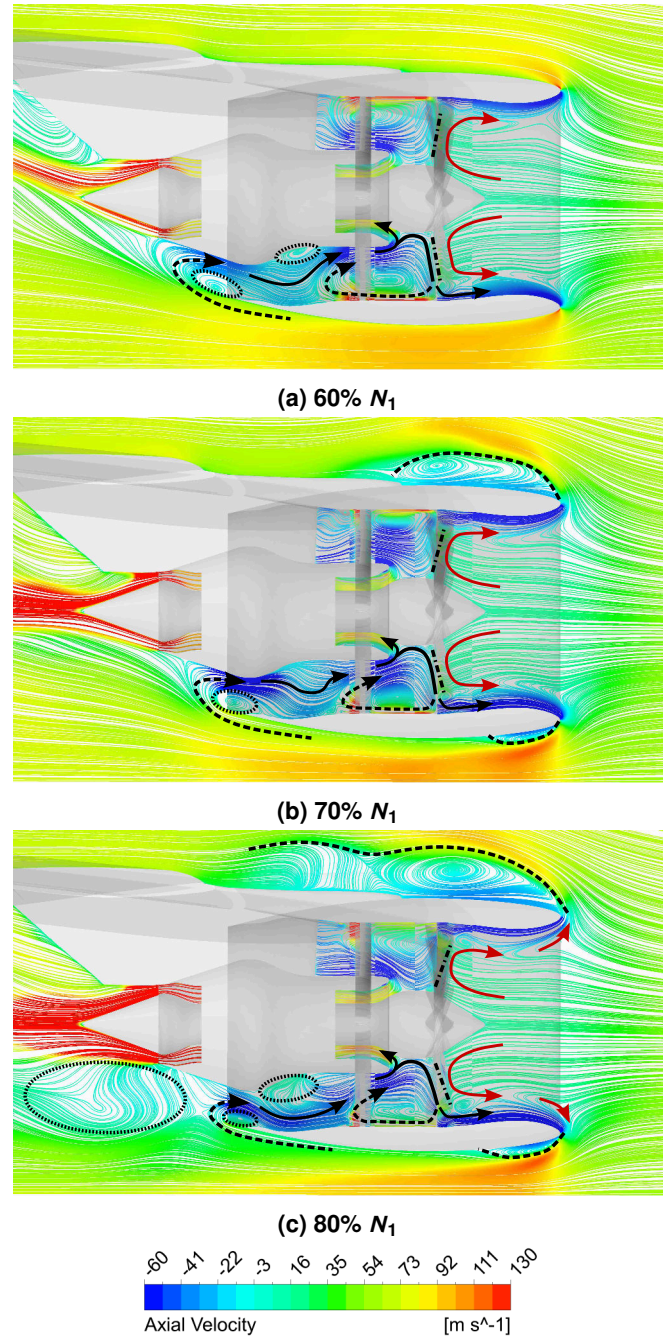


FIGURE 16: EFFECT OF FAN ROTATIONAL SPEED ON INTERNAL AND EXTERNAL TO THE ENGINE FLOW FIELD EVOLUTION AT THE END OF THE VPF TRANSITION USING VELOCITY STREAMLINES HIGHLIGHTED WITH AXIAL VELOCITY VALUES

thrust mode stagger angle setting. The total decelerating force at 80% N_1 is around 40% of the T_{MTO} , which is similar to the value noted in the reverse thrust estimation studies by the authors [15]. Additionally, the distortion into the core engine remains below the acceptable threshold values for stable operation at the higher rotational speeds as well.

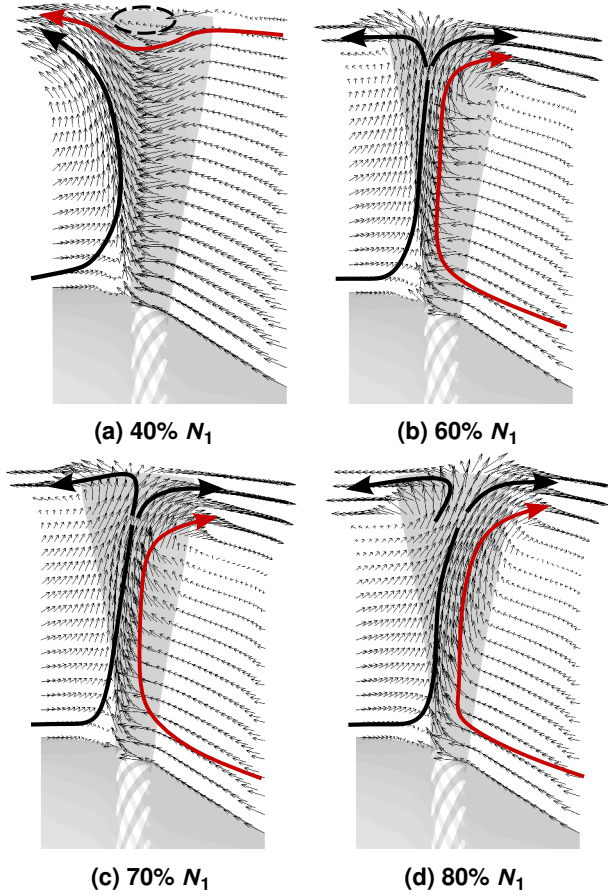


FIGURE 17: EFFECT OF FAN ROTATIONAL SPEED ON FAN FLOW FIELD AT THE END OF THE VPF TRANSITION USING MERIDIONAL VELOCITY VECTORS. FREESTREAM IS ANNOTATED IN RED WHILE THE REVERSE STREAM IN BLACK

5.3 Effect of Aircraft Landing Speed on Transition

The effect of aircraft landing speed on the evolution of the flow field during transition is described in this section. Two additional landing speeds of 120 and 160 knots, which represent typical minimum and maximum possible touchdown velocities, are considered at the typical 40% N_1 'Approach Idle' engine power settings. Since the fan power is the same for all the landing speeds, the core engine operating conditions are also identical.

The evolution of the ingested mass flow during transition for the different aircraft landing speeds is shown in Fig. 19. The ingested mass flow at each point during the transition indicates a decreasing trend that is proportional to the dynamic head of the freestream velocity with the reduction in the aircraft landing speed. This appears as a downward shift of the entire ingested mass flow evolution line with the landing speed reduction. This is because the amount of mass flow ingested by the engine at the nominal forward flow condition is proportional to the freestream dynamic head. Thereafter, the general profile of the mass flow evolution is controlled by the fan power setting and the temporal evolution of the fan stagger angle. Minor changes associated with the increase in the axial velocity at the fan inlet are observed not to significantly change the topology of the dominant flow

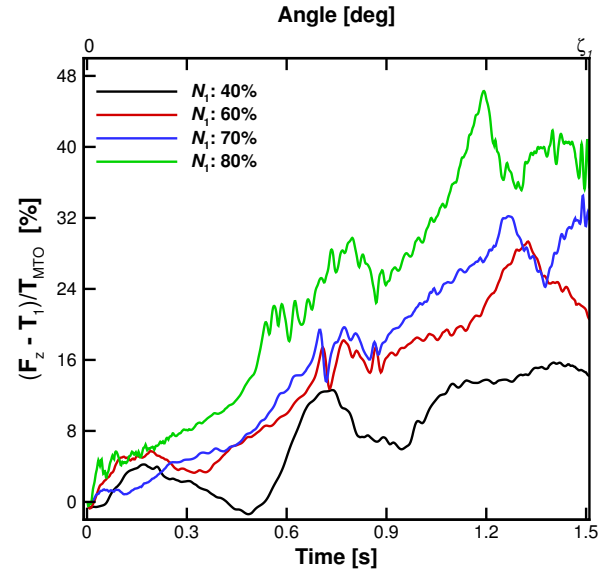


FIGURE 18: PERCENTAGE OF AXIAL DECELERATING FORCE EVOLUTION NORMALIZED BY THE MAXIMUM TAKE-OFF THRUST VALUE AT DIFFERENT FAN ROTATIONAL SPEEDS DURING VPF TRANSITION

features and hence result in a similar evolution of the flow field both internal and external to the engine. Consequently, the axial decelerating forces also change proportionally to the dynamic head with the shapes remaining similar. The distortion values into the core engine entry also remain within the threshold for stable core engine operation for all landing speeds.

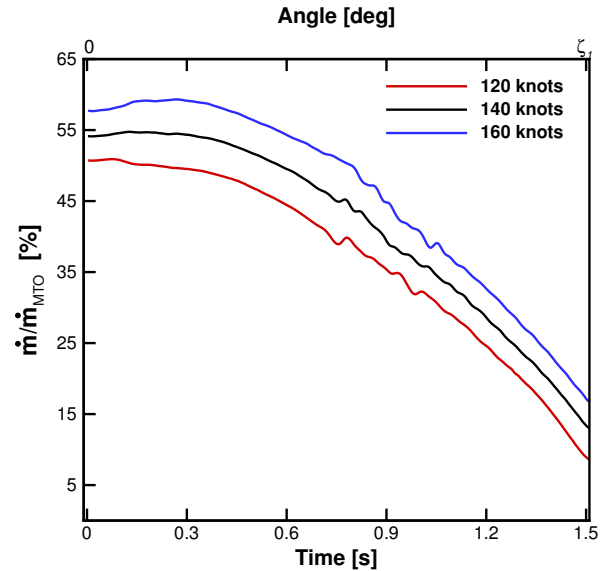


FIGURE 19: PERCENTAGE OF MASS FLOW RATE EVOLUTION NORMALIZED BY THE CORRESPONDING MAXIMUM TAKE-OFF VALUE AT DIFFERENT AIRCRAFT LANDING SPEEDS DURING VPF TRANSITION

5.4 Comparison: Transient & Steady-State approaches

A typical alternative to the fully transient simulation of the transition from forward to reverse thrust mode with gas dynamic and wall dynamic transients completely resolved, as in the present study, are steady-state runs that can be done for discrete aerofoil stagger angle settings during the transition. In order to effect this comparison, steady-state runs are carried out for 10 different stagger angle settings at 10 degree intervals between the nominal forward flow condition and the reverse flow stagger angle setting for the fan at 40% N_1 'Approach Idle' power setting at 140 knots aircraft touchdown velocity. The difference in mass flow ingested into the engine between the two approaches is shown in Fig. 20. The nominal forward flow condition is the same for both analyses because the steady-state solution is the initial condition for the fully transient solution. Thereafter, it is noted that at every stagger angle setting, the mass flow ingestion is underpredicted in the steady-state simulation. This error is initially low but progressively increases with the increase in stagger angle, except for an anomaly at the 60-degree stagger angle. This anomaly is hypothesized due to the spatial averaging in the steady-state runs.

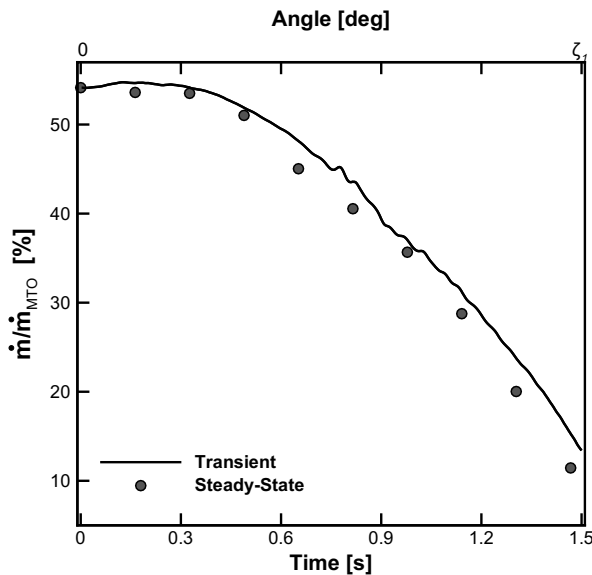


FIGURE 20: COMPARISON BETWEEN TRANSIENT AND STEADY-STATE APPROACHES: PERCENTAGE OF MASS FLOW RATE EVOLUTION NORMALIZED BY THE CORRESPONDING MAXIMUM TAKE-OFF CONDITION DURING VPF TRANSITION

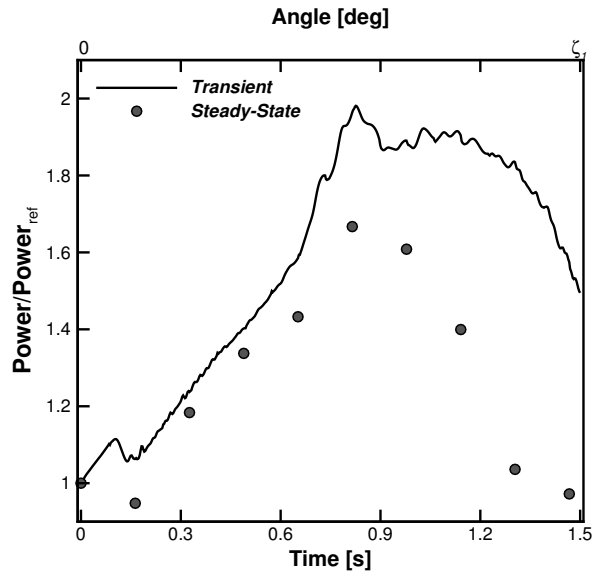
A comparative study of the flow fields from the steady-state and the fully transient runs indicated that at stagger angles beyond the middle of the transition where the flow is dominated by large separated regions and the formation of the reverse stream flow, the steady-state runs consistently overestimated the size of the blockages and the extents of the reverse stream. This is because in the transient transition simulations, the wall dynamics driven evolution of the fan flow field impacts the gas dynamics of the separated flow and the reverse flow. However, since the fan stagger angle is fixed in the steady-state simulations, the changes due

to wall dynamics on the gas dynamics of the separated and reverse flow regions are not captured. This causes a resolution of only a pseudo-steady gas dynamic effect, which tends to overestimate the blockage and cause a reduction in the ingested mass flow. Therefore, this difference is amplified further in the fan power absorption, as shown in Fig. 21a. The peak power is underestimated by more than 20% in the steady-state simulations because the blockage within the fan passages is allowed to develop to a larger size in a pseudo-steady manner leading to lower mass flow and improper total enthalpy change estimations. Similar differences of up to 20% are also observed in the evolution of the axial decelerating force, as shown in Fig. 21b. Most importantly, all the dynamics associated with the evolution of the decelerating force are not adequately resolved and the steady-state runs just indicate a near linear progression with the stagger angle setting.

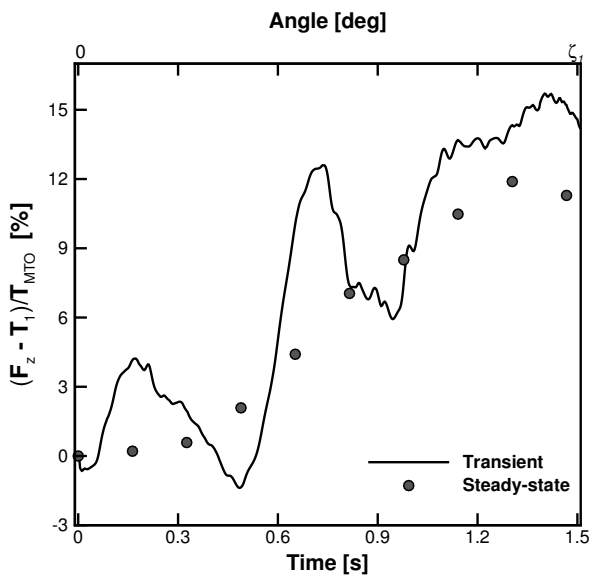
However, if the fully transient simulations are allowed to settle for another second at the reverse thrust stagger angle setting, the differences in all the parameters between the steady-state runs at this final stagger angle setting are less than 5%. Therefore, it is recommended that the fully transient transition be used to resolve the dynamics of flow transition, while steady-state runs may be used with known uncertainties for studying the fully developed reverse thrust behavior. Further reduction in uncertainties in the full reverse thrust mode can be achieved by using time-averaged unsteady solutions.

6. READ ACROSS TO OTHER DESIGNS

The discussion regarding the VPF transition from forward-to-reverse thrust in this study in terms of the evolution of the flow field in the engine, external airframe regions, fan, distortion into the core engine and decelerating forces on the airframe can be read across to other typical VPF designs. This is because the VPF design used in this study follows modern, conventional design practices with no specialised treatment of the flow coefficient-stage loading distribution to accommodate reverse thrust behaviour. This results in the aerofoils having typical shapes and stacking laws that are representative of modern design practice. Additionally, the key parameters that drive the behaviour are the fan pressure ratio and the rotational speed. In future high bypass ratio turbofans, for which the VPF as a proposition becomes attractive, the fan pressure ratio necessarily needs to be lower than 1.3 for bypass ratios in excess of 14 due to engine thermodynamic cycle considerations to have high overall engine efficiency. The VPF in this study has a forward flow pressure ratio of 1.27 and is representative of such future designs. The engine inlet diameter in the study is 110 inches, and the design fan tip speed chosen is typical of design practice, which makes the fan rotational speed to be in the conventional expected range. The transition to reverse thrust is considered to take place at typical 'Approach Idle' power settings and the effect of the transition at higher rotational speeds is also described. It is unlikely that the power setting will be lower than 'Approach Idle' for stable engine operation. The design thrust of the engine is 40000 lbf, installed on a typical 300-seater twin-engine airframe with a wetted surface area of ~ 4400 ft². All the results presented are non-dimensionalized with the fan design speed and maximum take-off thrust. The simulations are carried out at ISA, SL with 1 atm reference pressure and 288.15



(a) Fan power



(b) Axial decelerating force

FIGURE 21: COMPARISON BETWEEN TRANSIENT AND STEADY-STATE APPROACHES: FAN POWER AND PERCENTAGE OF AXIAL DECELERATING FORCE NORMALIZED BY THEIR CORRESPONDING MAXIMUM TAKE-OFF VALUES DURING VPF TRANSITION

K reference temperature and results in a Mach number of 0.21 for the 140 knots landing speed. The effect of the transition taking place at 120 and 160 knots, which are representative of bounds in landing speed and correspond to Mach numbers of 0.18 and 0.24 is also discussed. Therefore, conventional geometrical, turbomachinery quasi non-dimensional and kinematic scaling laws can be used to read across the results for other VPF designs [15]. Moreover, an exploratory study conducted to examine the effect of the time to transition from the forward to reverse thrust

mode, with two additional times, viz., 1 second and 2 seconds, indicated that the key flow features observed during the rotation are not significantly altered. The identified flow features appear at similar stagger angle positions as would be expected because the reduced frequencies of the flow phenomena are an order of magnitude lower than these typical time changes associated with possible transition actuation mechanisms.

7. CONCLUSIONS

A novel methodology that allows the fan blade aerofoils to rotate physically inside the domain has been developed and is used to characterize the installed fully transient flow field as the VPF transitions from nominal forward flow to reverse thrust mode. The effects of aircraft landing speed and fan rotational speed have been investigated as well as a comparative analysis has been conducted between steady-state and transient approaches. The outcomes of this study are the following:

1. Complete characterization of the time-varying flow field and detailed description of the evolution of flow features internal and external to the engine showing the conditions that the VPF is required to operate in at the beginning of the landing run. This is done at a realistic 'Approach Idle' engine power and captures the flow physics during the first stages of the landing run.
2. It is noticed that during the transition at a fixed rotational speed, the power absorbed by the fan doubles near the middle of the transition and eventually settles down at a value that is 1.5x the nominal power absorption when in the full reverse thrust mode. Similar spikes in power were observed by NASA in the static, isolated outdoor rig test during transition in the QCSEE program as well. Practical evidence for such torque increases in general aviation propeller aircraft that use variable pitch for thrust reversing is also well known to pilots. This is the first time that a computational study has been able to resolve and provide insight into the flow field while this happens. The implications of this increase in power absorption would need to be addressed in the core engine fuel scheduling if it is desired to maintain constant fan rotational speed. Most importantly, a predictive capability, albeit awaiting experimental verification at this stage, is available to build relevant control schedules for actual engine operation with the VPF. The ability to predict the distortions transferred into the core engine and the decelerating forces acting on the airframe during the transition into reverse thrust mode. The studies at typical landing conditions have identified no criticalities in terms of distortion for stable core engine operation. Moreover, the evolution of the decelerating force indicates characteristic peaks and troughs, the amplitudes of which are not significantly high enough to consider aircraft dynamic response.
3. Description of the flow field changes with the fan rotational speed and aircraft landing speed to account for plausible variations in the conditions encountered by the landing aircraft while the transition takes place. Additionally, this sweep in terms of fan power setting and aircraft landing

speed, which is representative of the back-pressure that the reverse flow would need to overcome, is an important aid for reading across to other VPF designs.

4. The additional advantage provided by the fully transient simulations that account for wall dynamics and gas dynamics as compared to steady-state runs carried out at discrete stagger angle settings is described. It is observed that the steady-state runs do not capture the dynamics in the airframe decelerating force and under-predict fan power by up to 25% primarily because of the pseudo-steady-state prediction of blockages, which in reality evolve with the wall motion. The resolution of wall dynamics is important because of the direct first order impact it has on the gas dynamic flow development with large separated regions of different reduced frequencies. Therefore, it is suggested that the qualification of VPF designs during transition for operability is better done by using a fully transient approach as in this study.

This study addresses an important part of the puzzle in dealing with a hitherto undescribed region of the operating envelope that involves the VPF transitioning from forward flow to reverse thrust mode. Therefore, the work provides valuable methodological approaches and discussions of the realistic operating flow fields during the transition that are necessary for exploring the feasibility of the VPF for generating reverse thrust in future, sustainable, environmentally friendly aircraft. At present, simulations are being carried out to capture the effects of the dynamic spool up of the VPF from the landing 'Approach Idle' conditions to typical reverse thrust power settings. The design of aerodynamic test rigs that can provide insight into the transition and reverse thrust behaviour is under development.

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APPENDIX A. ROTATION METHODS OF FAN BLADE AEROFOILS

The following illustration shows the two repitching option of fan blade aerofoils.

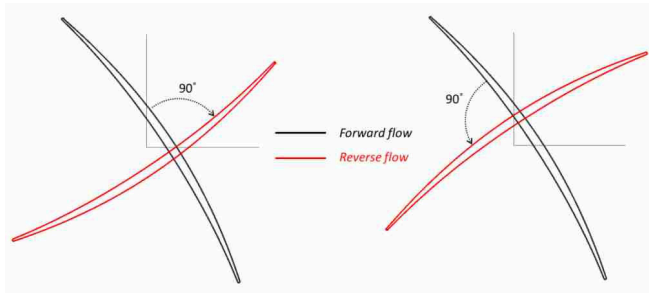


FIGURE 22: SCHEMATICS SHOWING CLOCKWISE ("THROUGH-FEATHER") AND COUNTER-CLOCKWISE ROTATION ("THROUGH-PITCH") OF VPF BLADE AEROFOILS TRANSITIONING TO REVERSE THRUST MODE [15]



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On the flow physics during the transition of a variable pitch fan from nominal operation to reverse thrust mode

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